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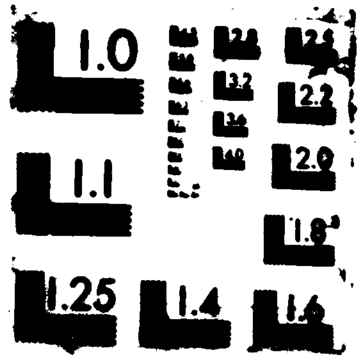
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The Environmental Qualification Specification as a Technical Management Tool

Charles T. Morrow

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CHARLES T. MORROW

Consultant

Prepared for
THE SHOCK AND VIBRATION INFORMATION CENTER
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FOREWORD

Environmental qualification specifications prescribe shock and vibration conditions for use in test at the end of development as a verification of design adequacy. We do not often consider that such specifications can also serve as technical management tools during the development process. Although these specifications are not used so much during the initial design, they nevertheless stimulate the customer and contractor program offices to plan for developmental effort in shock and vibration. They also often inadvertently limit the scope and creativeness of such engineering. To my knowledge, this report is the first study on the effectiveness of qualification specifications in this technical management role and on means for improving this effectiveness. The author shows that there are tradeoffs between design adequacy verification and reliability achievement--what appears to serve one objective best does not necessarily suit the other. The result is that, beyond some point, these may become opposing rather than complementary objectives. This report is neither a treatise on theory and technology nor a manual for detailed design after initial engineering decisions have been made. Instead, the report is intended for any reader, administrative or technical, who influences initial decisions concerning shock and vibration approaches, or the specifications and accepted practices underlying such decisions. It may be particularly useful to those who are held responsible for the consequences of such decisions.

In my opinion, Dr. Charles T. Morrow is especially qualified to write a report of this kind. I first met him in 1952 when he was one of the pioneers who brought about the introduction of random vibration testing in the missile and aircraft industry. In the early days and over the years, he has introduced many innovations in the area of shock testing, particularly in relation to the concept of the shock spectrum. Having worked on programs for Hughes Aircraft, Ramo-Wooldridge Corporation, Aerospace Corporation and others, he has had extensive experience in the development and use of environmental qualification specifications. In 1963, Wiley published his book on Shock and Vibration Engineering, in which he introduced some concepts of decision making that are expanded in this report.

Let it be clear that the reader will not find all the answers to this complex problem in this document. But, to me at least, Dr. Morrow has done a good job of putting the problem in its proper perspective, and he has proposed some solutions. Only time will tell whether these are the best solutions, whether they can lead to a development approach that will be effective and at the same time economical. I ask only that the readers keep an open mind, then send us comments and suggestions. We would be pleased to receive them.

Henry C. Pusey
Shock and Vibration Information Center
September 1981

PREFACE

In the interval between initiation and completion of the present study, regulation of industry by Government has emerged from a period of enthusiastic expansion into a period of cutting back and rethinking, and this sets a new stage for the review of Government specifications as well. Government environmental specifications, intended primarily for Government contractors, are in many respects analogous to Government regulations on noise control, intended for industry in general. The former are necessary, and I am not indicting the latter -- I contributed to the vote that established the Institute of Noise Control Engineering, which, in cooperation with the Environmental Protection Agency, has led to establishment of many noise control regulations, and I generally support INCE objectives. But the change in attitude toward regulations and the arrival of a period of austerity reinforce my contention that environmental specifications should be reviewed for cost/effectiveness in relation to their most basic objective. This objective should be obvious -- improved product reliability and performance under the conditions of transportation, storage and use. Yet, specification review has been limited to date to considerations of scientific aspects of environmental test and, to a greater extent than most participants would rush to admit, of past tradition or precedent, whether or not it makes adequate sense from either a scientific or technical management point of view. Impact on design and development has been ignored. Improved effectiveness of environmental specifications in the most basic sense is not an easy objective, but the customer-contractor relationship carries some customer privileges which can be used judiciously. The first step is to find where we are so we can start from there. The second step is to formulate practical recommendations.

The work reported in this book started out as an evaluation of shock and vibration specifications in the more restricted area of design of isolation systems and shipping containers. It was based on interviews of people in Government and industry who, in one way or another, were involved in decisions concerning these problems. The question was not merely whether the specification requirements were scientifically valid, but what they induced managers and engineers to do, and whether these actions were satisfactorily constructive.

The interview survey provided useful insights, not only into this initial problem, but also into the effectiveness of specifications, as now written, in the total area of equipment shock and vibration engineering. Isolation and packaging are not entirely separable from the rest of shock and vibration engineering.

When a Government agency supports development of equipment or buys the products, there is essentially one customer and one contractor. The contractor, after the proposal and selection stage, is not subject to the motivations of a competitive market. Consequently, to help ensure a satisfactory product, the customer writes or invokes specifications which directly or by implication become part of the contract. These typically place requirements on the prototype or product, prescribe tests that the prototype or product must pass, and prescribe to some degree how design is to be accomplished.

Specifications are absolutely necessary, but they make each product and its development more expensive than it would be if development were for a competitive market. While they generally lead to higher quality, this is not necessarily proportionate to the cost, and frequently an item of equipment that complies with all requirements may be unsatisfactory in some respects. In fact, requirements, from time to time, may obstruct competent engineering.

With the present pressure to hold down Government budgets and to obtain the most for the development dollar, this problem of the effectiveness of specifications is as important as the development of new technology. Yet, it has received essentially no systematic study or evaluation. Therefore, even with the most competent people on behalf of both customer and contractor involved in negotiations, there has been little opportunity to make significant improvements.

Probably the first step in a constructive direction was Col. Ben Swett's evaluation of statistical reliability test specifications, discussed in more detail in Chapter 5. It was based on questions of compatibility with environmental specifications and of capability to predict field reliability. The present report goes further by examining more directly the actions taken in response to environmental requirements. The recommendations given here focus on direct stimulation of more constructive engineering effort early in development programs, at minimal cost, and in such a way that prototype evaluation at the end of development may become a less critical procedure.

Does this mean that the Government should prescribe in detail how engineering decisions are to be made? Emphatically no. The Government has inadvertently attempted this in connection with packaging for shipment -- with disastrous results. The applicable specifications succeed in making decisions difficult, without actually tailoring the various containers for individual needs, or even considering all factors important to design. The Government should be cautious about taking the responsibility for the Contractor's engineering decisions. Chapter 1 introduces a better idea and Chapter 5 develops it.

The recommendations, with some modification, might be useful in noise control also but cannot be incorporated directly into regulations, because the Government is not the usual customer. However, if the recommendations are expressed in form for use, tested for effectiveness, and accepted for shock and vibration, a more informal adaption to noise control may in time be beneficial. Both fields can benefit from systematizing the development approach. The methods that are most cost effective for this phase are simple, unglamorous, with a large measure of intuition, and therefore are of minor interest to scientific societies that are absorbed in expanding the frontiers of knowledge.

As the author of many papers and the principal author of a pivotal environmental specification, I have had the privilege of inducing fundamental changes in shock and vibration engineering, but I have been aware from the beginning that fundamentals were not the only challenge. I now consider it a privilege to be able to exert some influence from a different point of view.

I appreciate the support of the Shock and Vibration Information Center and in particular the patience of its director, Mr. Henry C. Pusey, with the early drafts, and his constructive editing of the final draft. However, the opinions expressed in this report are my own and do not as yet represent policy of any Government agency.

Charles T. Morrow

DEDICATION

to Irwin Vigness

of the Naval Research Laboratory

a distinguished and widely respected pioneer

from whom I first learned about shock

as the Navy understood it, and from whom I first gained

an appreciation for the practical constraints

on shock and vibration engineering.

CHAPTER 1

INTRODUCTION TO THE FINDINGS AND RECOMMENDATIONS

This report is based for the most part on a one year survey, funded by the Shock and Vibration Information Center, of decision making in the specialties of isolation and packaging. For clarifiction, isolation is an attempt to protect equipment against mechanical vibration and shock during use or while it is installed for use. Packaging deals with protection during shipment. The survey was carried out by a series of person-to-person interviews. It was not confined to shock and vibration engineers, but included others who were in a position to influence the decisions.

The results are reported and interpreted in Chapters 2 and 3 -- two chapters because there are specifications explicitly applicable to packaging but isolation is merely an incidental aspect of equipment qualification specifications. In both cases, the decision process was found to be chaotic and ineffective, largely because the decisions are for the most part interorganizational problems and precedent allows only the literal wording of the specifications to be applied in negotiations, with little opportunity for engineering insights. Recommendations for change in the specifications to improve the cost/effectiveness ratio of these specialized decisions are given in Chapter 4.

By far the most important part of this report is Chapter 5, which contains at its beginning some recommended changes in MIL-STD-810 and related specifications to improve the cost/effectiveness of shock and vibration engineering more generally, followed by clarification and discussion of the recommendations. There is a brief commentary on a presentation by Col. Ben Swett on inconsistencies between MIL-STD-810 and MIL-STD-781, as an illustration of the need for occasional review of specifications beyond the traditional process that has been used in their approval. Isolation and packaging are merely technical specialties within shock and vibration engineering in general. The effectiveness of specifications could not be low in the more specialized areas without being low in the whole.

Environmental qualification specifications such as MIL-STD-810 have fundamentally had the double purpose of stimulating engineering effort during development and providing a check on design adequacy at the end of development. For shock and vibration environments, the former is seldom achieved. The reader may know of exceptions and so does the author, but they are not common enough to establish a definite pattern. Therefore, it is recommended that qualification specifications become instead <u>development and qualification</u> specifications. This means that they should call also for a shock and vibration development program appropriate to the particular equipment under development, so that it can be <u>proposed</u> by the contractor, <u>negotiated</u> with the customer, and <u>funded</u> by the customer.

Part of the problem has been that it has been difficult to establish an adequate development approach that would be effective and at the same time economical. Chapter 5 and Appendix 4 propose a solution to this problem. It involves a proposed resonance frequency measurement technique which did not originate in shock and vibration engineering at all, but was worked out by the author in the late forties during the development of a tuning-fork gyroscope at the Sperry Gyroscope Company. No reliability problem was involved. If the various resonances of the instrument were not measured and appropriately detuned from the fork frequency, the instrument invariably had an intolerable drift rate. The instrument never reached production, partly because it would have required extensive further development to catch up with the wheel gyro in inertial guidance applications, and partly because in less exacting applications it required more electronics than the wheel gyro. At that time, this was an important consideration. However, the frequency measurement technique and the detuning technique have proved to be powerful and economical as part of an approach to the shock and vibration development problem.

Publication of this report was delayed by funding difficulties. Chapters 2, 3 and 4 remain essentially as first written. Chapter 5 has undergone evolution in the meantime, partly because the recommendations deserved more thought than had been possible at the time of the early drafts, and partly because of another movement to modify specifications. It was not clear for some time whether Col. Swett's influence would result in combining MIL-STD-810 and MIL-STD-781 into one specification, which would have greatly complicated the recommendations of the present report, or merely in revising MIL-STD-781. That movement has run its course and has resulted in a much improved MIL-STD-781 while leaving MIL-STD-810 serving its original role. Consequently, much tentative discussion of the statistical reliability testing problem that was in the early drafts has been deleted, leaving only enough to provide some additional perspective on the present recommendations.

It is a thesis of this report that the merit of a specification should be judged primarily, not by its technical validity (although this remains important), but by the quality of engineering it induces. At the present time, specifications such as MIL-STD-810, as now written, inadvertently obstruct much of the engineering they were intended to stimulate.

1.1 The Survey

To obtain information for this report, the author visited various customer and contractor facilities in various parts of the United States to conduct meetings in which the participants were confined primarily to the discussion of initial decisions, or in other words joint interorganizational decisions, regarding isolation and packaging as opposed to more detailed work carried out typically within a department or section. The participants are listed in Appendix 1. The meetings were in effect small panel sessions with the author as moderator, and designed to stimulate free discussion, rather than to solicit answers to a preconceived set of questions. At the beginning of the first meetings, a tentative list of questions, reproduced in Appendix 2, was handed out as a preliminary indication of the type of considerations of interest for discussion. This was soon abandoned, except for spasmodic use by the author himself as a partial check on whether there might still be important matters not yet brought up. It became much more effective in stimulating discussion to recount early experiences of the author or findings at previous meetings. Often this produced nuggets of information that could have been obtained in no other way. The participants were assured that they and their organizations would not be identified with particular viewpoints expressed in the findings unless for some special reason it was agreed by those concerned that this would be desirable. In the privacy of the meetings, however, restraint on identification of people or organizations was not allowed to inhibit free discussion.

The wholehearted cooperation of the participants, both in making their time available and in contributing their experiences and reactions, is sincerely appreciated. There was never any indication that they were reticent, and sometimes they were surprisingly open-minded on subjects such that this might not be expected. Although all initial contact at the various organizations to be visited were enthusiastic and cooperative in setting up meetings once the project and its association with the Shock and Vibration Information Center were identified, they seldom actually had a clear idea of the objective until a meeting got under way. Consequently, the mix of participants or responsibilities was very variable. On more than one occasion, the shipping container problem came to be discussed primarily by equipment designers and structural engineers. In formal negotiation of shipping container design characteristics, these participants would normally be adversaries to the packaging engineers to some degree, but none of their expected bias showed up. On being asked how they would want to go about packaging design if they acquired such responsibility, they showed surprising perception for the constraints on the packaging engineer, and sympathy for his difficulty in obtaining reliable environmental and fragility data. They were as perplexed as the shipping container specialists about the practical difficulty of the problem.

1.2 The Findings

In Chapters 2 and 3, which have much the character of a moderator's report or summary, great care has been taken to distinguish the actual findings from the author's explanatory comments. The findings are reported, to the best of the author's ability, essentially as expressed to him at the meetings that he scheduled and to which he travelled -- but as a synthesis of overall findings rather than as a series of meeting-by-meeting reports. His immediate notes on each meeting were brief, as note taking could be so overemphasized as to stifle discussion. After each meeting, the notes were reviewed and supplemented, with the intent of making them as complete a record of the important points as possible. Eventually, the individual meeting notes were combined and summarized to yield the findings of Chapters 2 and 3. Often, the same thought was found to be expressed at many meetings, but not in exactly the same way. Typically, discussions of the same problem at different meetings were overlapping rather than coincident. But, to the best of his ability, the author has reported the essence of the observations of the participants without coloration from his particular point of view or prejudice. The author's explanatory comments are italicized, so as to be distinguished from the findings by format, and are labelled as comments. These undoubtedly are colored, the author hopes beneficially, by his particular point of view.

1.3 The Recommendations

In Chapter 4, recommendations are made toward the improvement of isolation decision procedures. Then various options for the improvement of packaging decision-making are offered, and then crystallized into recommendations. Finally, recommendations with a much broader applicability are given in Chapter 5.

It became evident that in interorganizational negotiations, inadvertently constrained by the language of specifications, shock and vibration are treated almost entirely in terms of level of severity, as if they resembled temperature or humidity. The particular frequencies at which shock and vibration are most dominant, or at which equipment under development are most vulnerable, are almost never considered. This bypasses what should be the essence of shock and vibration engineering and leads to engineering blunders, extra costs, and schedule delays. Since it is not practical to consider these frequencies routinely in specifications for environmental test, it is recommended that the specifications call also for an engineering development program in which measurement and detuning of the frequencies is expected to be carried out as far as is appropriate for the particular equipment under development.

1.4 Conclusion

This is the first survey ever carried out to evaluate environmental specifications as technical management tools -- in other words in terms of what they induce management and engineering to do in response. People who have participated in the past in the preparation of specifications have not had the benefit of such a survey. The intent of this report is to evaluate the effectiveness of existing specifications and recommend changes in them for the benefit of specification writers, rather than to criticize the writers.

It is illuminating to compare the role of current shock and vibration specifications in more depth with that of noise control regulations.* The two types of documents are similar in that they relate to the same fundamental technology -- both fields involve interchange of energy between mechanical energy and sound, as well as propagation of both forms of energy. Both types of documents focus on tests, and they both tend to induce after-the-fact patch-up cures rather than orderly development. They differ in that noise control tests are designed to <u>measure</u> environment, whereas shock and vibration tests are designed to measure performance and survival in <u>prescribed</u> environments. In noise control, moreover, the ear cannot be redesigned -- the objective of corrective action is to <u>modify the environment</u> as necessary. In shock and vibration, the environment, except when isolators may be used, is considered to be beyond engineering control -- the usual objective of corrective action is to <u>ruggedize the failure points</u> as necessary.

In structures (airframes etc.) shock and vibration effort has emerged naturally out of the stimulus of catastrophic failures. But, shock and vibration, as applicable to equipment, is one of the few engineering fields that has been created entirely by specifications. Its virtues and limitations correspond to the virtues and limitations of the specifications.

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*C.T. Morrow, "Noise control versus shock and vibration engineering", J. Acoust. Soc. Amer., Vol 55, No. 4, April 1974, pp 695-699.

CHAPTER 2

FINDINGS ON PACKAGING FOR SHIPMENT

The meetings for collection of information typically gravitated more toward protection of equipment by shipping containers than isolation of equipment for its intended use.

It is usually management policy, in Government and in Government-oriented industry, to design equipment solely for the environmental conditions of use and place on the container engineer the entire burden of providing protection against the shipping environment. Presumably the rationale for this has been that the adequacy of equipment for its intended use should not be compromised by design for the transportation environment -- in particular, its weight should not be increased. But there has been no careful comparison of the two environments, nor any inquiry into the degree to which design for the environment of use may make equipment generally adequate for the shipping environment, nor any investigation into what weight increases might really be necessary. Little or no responsibility has been placed on the equipment designers to provide the packaging engineer with information about the equipment as a basis for decisions concerning the container, beyond the quoting of whatever environmental specifications were decided on prior to the design of the equipment.

A Government shipping container is usually, in itself and in addition to its contents, a deliverable item even if not from the same source of supply, *and therefore subject to its own specifications*. Under tacit pressure from management, the writers of specifications for the design of special containers for equipment that may be suspected of being fragile have tried to adhere to a scientific method. They have required that the container design be based on a comparison of the equipment fragility (i.e. the shock and vibration accelerations that, applied to the equipment mounting points or support points, will barely cause damage there or in the interior) with the shipping environment. This environment is represented, not by reliable data, but by specified vibrations and drops, based on data taken and reduced as much as three decades ago, when shipping environment data acquisition and reduction were even more unreliable than they are now. Even so, the fragility estimates supplied by the equipment designers are much more suspect than the specified environments. The decision process for establishing the basic design of a container has an appearance of scientific method. But deeper examination commonly shows precedent and expediency to be the controlling factors in the way the legal requirements are met.

The remainder of this chapter describes the reactions of the various people interviewed to this general problem, gathered under various appropriate headings, and followed by the author's comments and interpretations.

2.1 Fragility

The prevailing reaction was that the use of fragility in a quantitative sense* is not a satisfactory procedure for decision making. Only one engineer strongly defended the approach of comparing fragility levels with shipping environmental levels as a routine approach to the design of containers. Another engineer was skeptical of fragility estimates as generally acquired and used, but expressed strong discomfort at any simplification of procedure that might exclude them. It was pointed out by others that the fragility of a missile in a container will depend on how it is to be supported, which may or may not have been considered by the missile designers. Several engineers attributed the bulk of failures in shipment to cantilevered assemblies, either within the contents of the container or as a result of the means of support for the contents. Nevertheless, it was generally claimed that the designers of the contents, especially aerospace engineers, tend to be extremely conservative in response to requests for fragility data, and to quote permissible environmental levels that are too low, and often related to operational rather than non-operational requirements.

In response to a container specification that requires comparison of fragility with environment, the detailed contractor practice varies from organization to organization. At one extreme, the packaging engineer is required to request data from the designer and use it as received. The designer is permitted to quote only official design or test specification levels. On the other hand, the packaging engineers of at least one organization are privileged to apply correction factors to increase levels so as to compensate for estimated designer conservatism. In another organization, the packaging engineers are privileged to make and use their own fragility estimates.

Local policy on design of the contents also affects the difficulty of the container decision problem and the effectiveness of the solution. At one extreme, the contents are designed only to in-use conditions; the container must provide protection for any shipping environment levels appearing to exceed these conditions. However, some contractors prescribe design acceleration levels of 10g or more for the low frequency range, not subject to verification by test. The designer may be encouraged to negotiate if the prescribed level will actually cause him difficulty.

At one organization where a strict formalism is adhered to on fragility estimates, it was reported that accidents, occasionally happening during assembly and test, result in shock environments well in excess of any design or test figures. Usually, the item is found to be undamaged. If so, it is subjected to a vibration test as a check on possible susceptibility to fatigue. If it survives this, it is treated as a deliverable item, at least as a spare. But using such data as are available on the accident environments as a basis for increasing any fragility estimates is not permissible.

Yet, one organization concerned primarily with space payloads does not consistently use flight or test input environments, as stated in official

*Appendix 3

documents, directly as fragility estimates. For initial design of each portion, the quasistatic flight accelerations (based on atmospheric turbulence, etc.) are multiplied by 220 and divided by the square root of the weight in pounds. It was claimed that this was very nearly adequate to ensure survival of eventual shock and vibration tests, without significant weight penalty. The acceleration figures from the procedure remain available as points of departure for fragility estimation. This interesting case will be discussed again in Section 2.5

The same organization reported use of some design guides based on first permissible resonance frequency* (as a supplement to minimum static load) as follows:

Major electronic assemblies	325Hz
Small assemblies	400Hz
Small subassemblies	1000Hz

Few engineers actually questioned the need for shock protection of contents in shipment. Many shock and vibration engineers claimed that any sensibly-designed device should be able to survive the shipping vibration environment without protection. However, there was one report of a large vacuum tube that failed repeatedly from shipping vibration because the metal spring shock isolators of the container were undamped. As in the case of in-use isolation, the particular organizational plan, and the degree to which different groups have developed a capability to work together harmoniously, affect the difficulty and effectiveness of container design decisions.

Sometimes an impasse on container design between contractor and customer can be resolved by compromise if there is something to trade, such as cost. In some instances there are official gross weight or size limits which help bring about a compromise. There are official size limits for some shipboard containers. But more typically there are no official size or weight limits.

Comment

The engineer who strongly defended the fragility-environment comparison was involved with shipment only of devices for use in space. These are low manufacturing quantity, extremely high cost items. Special investigations to obtain data for packaging engineering are easily absorbed financially, and special precautions in shipment are feasible.

The engineer who mistrusted fragility estimates but expressed discomfort at any decrease in their use did not actually use them extensively himself. He used tensile strengths at failure points, etc., rather than fragility referred back to mounting points or other support points. He was involved in packaging of contents of such a nature that leakage of nuclear material was the primary hazard to protect against. Because of the cost of the contents and the seriousness of the hazard, funding for modelling studies, environmental analysis,

*Appendix 4

instrumentation of shipped articles, etc. it is not difficult to obtain. The general absence of subtle malfunctions as a possible consequence of shipping damage, as a consideration, makes failure points relatively easy to identify.

A missile cantilevered in its container may well be even more fragile than the design loads for flight suggest. However, cantilevering can be avoided if the design and packaging teams are required to communicate and negotiate early enough in each program. In fact, if there is sufficient mutual understanding and cooperation, it may be possible to design the supports so the first lateral modes of the airframe are not excited by the transportation environment.

The claim that designers tend to be over-conservative in fragility estimates should be accepted as generally true but should not be taken as an adverse criticism of the designers. They cannot afford to be vulnerable to criticism in the event of shipment damage. The data they supply become part of a formal record, typically involving the customer as well as the contractor. Consequently, the designer cannot dare do much more than quote numbers from official design and test documents, and indeed may not be permitted to do more, unless local policy is such as to relieve him of some vulnerability. But the fact that a device has survived a test only up to a specified environment does not prove that a moderate increase, at low frequencies, would cause failure.

Similarly, a packaging engineer does not dare do much beyond acceptance of fragility figures as quoted unless local policy provides some protection from personal vulnerability.

Such protective policies put project management in the position of sharing vulnerability with subordinates, and persist only if there have been no serious difficulties from damage in shipment in consequence.

Policies on design for in-use environment only, versus design for transportability as well, always come about, at least in part, for expedience - as intuitive decisions or tradeoffs on the basis of the insights of the local technical managers. The practice of supplementing in-use environmental requirements by a minimum g-level acceleration for low frequencies seldom affects the design of the hardware to be shipped, but does affect fragility estimates. It, in effect, directs that the estimate shall not be less than the supplementary g-level unless there is good reason.

The practice of multiplying flight loads by 220 and dividing by the square root of the weight, for initial design, and to obtain fragility estimates, is significant from several points of view. It is more common to use equivalent static accelerations, based on specified shock response spectra or perhaps on three times estimated rms responses to specified random excitation, as informal design objectives. But no instance of such numbers being available as points of departure for fragility estimates was discovered. Although entirely empirical, the mass-dependent design loads of the present finding are more sophisticated in some respects, and are based on years of trial and evaluation. For pursuit missiles, with higher boost and maneuvering accelerations, smaller proportionality constants would be more appropriate. It is striking that the one example of fragility estimates, derived from, but greater than the flight loads was found in connection with space hardware of the most critical nature. Only three items of a kind are made -- two to fly and one to serve as a spare.

The design guides based on frequency are a valuable supplement to those based on equivalent static load. Such ideas should be explored more generally as a means for minimizing redesign necessary after environmental test.

Quite possibly most devices to be shipped can survive the vibration environment without dynamic protection, although this was contested by one reviewer of this manuscript. However, an isolator installed in a container to control peak shock accelerations must have some damping incorporated. Otherwise sustained vibration can cause frequent hard bottoming and consequent damage to the contents.

Furthermore, it is not literally true that any sensibly-designed device can survive the shipping environment without protection. For cost-effective container engineering for devices made in quantity, the important considerations are to distinguish between typical and particularly fragile contents, maintain a methodology that simplifies decisions for the former, and provide simple but adequate approaches to the latter. The contents are seldom fragile in the low frequency range merely because of weight limitations on design, but critical functional requirements for the use of the contents may lead to design features that must be fragile. For example, ball-bearing races in inertial gyroscopes may Brinell during shipment to such an extent that drift rates in use become excessive, either immediately or because of rapid wear while in use. Such critical requirements on design should be the major considerations in distinguishing between typical and particularly fragile devices.

2.2 The Transportation Environment

There have been some spasmodic and some extensive measurements of transportation environments in recent years. The data readily available to packaging engineers were subject to some criticism for being measured at locations where containers would not normally be stored, or measured on rather flexible structure in the absence of dynamic loading by any container. Peak acceleration meters were claimed to be misleading, as they often respond to high accelerations of short duration and no significance. For all reasons, envelopes of the acceleration data were believed to be over-conservative.

It was pointed out that the environment of a manned vehicle cannot exceed the fragility of man. In one meeting, it was claimed that the largest acceleration ever observed on a truck trailer with air-cushion ride was 1.5g. However, in another, it was claimed that the ride could be rough for light loads or with poor control of air pressure. It should be noted that humans are fragile primarily in the frequency range below 50Hz, whereas equipment is typically more fragile above 50Hz.

Vibration specification requirements for shipping containers encountered some criticism as being based on data twenty or more years old. However, there was little comment on how specified swept-sine levels should be changed. Dwell tests requiring fixed-frequency excitation at isolator resonances for ensurance against isolator fatigue in shipment drew strong criticism for overheating the isolators. Some specifications permit intermittent vibration in test to reduce this effect.

The primary shocks of concern while the contents are in the container are drops during handling by man or machine. These could occur from any height, the probability of occurrence decreasing with height. Secondarily, there is concern with humping -- the assembly of railroad cars into a train. This operation was reported to involve speed differentials of 5 to 10 miles per hour, corresponding crudely to drops of 2 to 4 inches. The humping acceleration was reported to resemble a half-sine wave of 10 to 20g peak acceleration and .05 to .1 sec duration with superposed "hash" or transient motion at the higher resonant modes of the cars.

Extreme difficulty was reported in the shipping of large shakers (for vibration testing of aerospace hardware) by railroad, not because the shakers were fragile, but because the crated shakers tended to break loose and slide about the car floor.

The test specifications most frequently applicable to containers for contents, such as small missiles, require shocks in the form of drops to a hard surface from heights up to three feet or less, the maximum drop height being in inverse relation to gross weight. There was almost no explicit criticism of these drop heights. Sometimes several items are carried in the same container, within the same isolated cradle, in order to reduce the ratio of container volume to contents volume.

But one organization questioned these drop heights and emphasized that more damage results from shipment by air than by any other primary mode -- for two reasons. There are more transfers required. Drops incurred in loading an airplane are higher than in loading any other vehicle.

For space hardware, manufactured in small quantities, it is possible to control the actual shipping environment by various methods, including the modification of commercial vans and the routing of trucks in caravans to avoid impulsiveness of individual drivers. Other precautions are discussed in Section 2.5.

Humping is simulated by a half-sine wave of acceleration. In verifying the pulse shape on an oscilloscope it is usually permissible to use an electrical filter between the accelerometer and the oscilloscope to suppress from the display the "hash" developed by the shock test machine. In other words, this hash is not considered relevant to the test.

In most of the vibration and shock tests for containers, it is permissible to use dummy contents with weight distribution and external geometry similar to those of the actual contents. At least this is permissible if the actual intended contents are not available at the time of the container test for its design acceptance. The dummy contents are instrumented with accelerometers so that it can be verified that the transmitted environment does not exceed the official fragility estimates.

There is a notable exception to this criterion in connection with missiles for shipboard use - a 40 foot drop for which the actual missile complete with rocket motor and warhead are required to be in the container. This is not a test for damage protection for the contents, or even ruggedness of the container, but purely safety for the ship and crew in the event of an accident. This test was reported to simulate a drop from a hangar deck to the flight deck of an aircraft carrier.

Several environments are occasionally damaging to container and/or contents during transportation but are not explicitly reflected into general specifications and seldom influence the design of container and contents. These include transfer at sea, delivery by helicopter, and collision between a fork lift and a container. The possibility of cargo breaking loose in the hold of a ship affects the design of tie-down devices for securing the containers but is not reflected into design of internal protection for the contents.

Comment

The dwell test for fatigue of the isolation system in a container is intended to be an accelerated test, in order to save test time and cost. Even for a moderately-accelerated vibration test, establishment of a valid increase in level would be difficult. For the dwell test, the test times are minute by comparison with the possible duration of the actual vibration environment, and the vibration far more severe. This compounds the problem. With temperature rising well beyond the range normal in transportation, the effect of the dwell test may be more of a chemical disintegration than a fatigue.

The humping speeds and the acceleration pulses do not check each other if the mechanism of humping shock is interpreted as a simple deceleration, or a simple acceleration to the speed of the train. Evidently the shocks are amplified by the first resonances of the railroad cars.

The relation of drop height to gross weight is based on the assumption that manual handling as opposed to machine is more likely for smaller packages, but this may not be pertinent to environments associated with the loading of an airplane.

If the humping test shock were to be applied directly to the contents, as though a rigid support within the container, the hash should be considered part of the shock, and no filter to suppress the hash in the signal to the oscilloscope should be permitted. Rather, there should be spectral specification requirements in the frequency range in which hash may appear. However, if the support within the container is an isolation system or cushion, and it can be assumed that this does provide effective isolation at the higher frequencies, the use of the filter can be considered permissible for the sake of a beneficial simplification of test procedure. Should there be a failure in test, however, the hash should be examined as a possible spurious cause.*

For routine acceptance of container designs, there is a beneficial simplification of procedure in separating container testing from contents testing.

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*Chapter 5, Section 5.5

The use of dummy contents permits packaging for shipment to be considered earlier in a program. This in turn can be more favorable for exchange of information and for negotiation between contents designers and packaging engineers. Dummy contents that are dynamically similar to the actual contents are adequate for instrumentation to measure transmission. The specified test environments and the fragility estimates are not sufficiently refined to demand extreme realism in all the test hardware. The actual contents would be advantageous, not in routine container acceptance test but in a special test to destruction of the contents for the sake of whatever information may be obtained. They are essential, however, in tests for safety in extreme drop.

2.3 Missile Transportation Accidents

Two accidents were reported in which missiles in their containers survived environments that were well beyond those considered in the design of either the missiles or the containers. This sheds doubt on whether present container design methods are worth the effort, especially as routine requirements.

In the first accident, the container and missile were on a sling 10 feet above the deck of a ship. The container, which was about 14 feet long and about 1 ton in gross weight, failed a rivet, and dropped to the deck. There was damage to the container by the missile fins and damage to the fins. Otherwise, the missile, complete with rocket motor and live warhead, was unharmed. Any missile overdesign implied by the accident report was defended as beneficial for safety.

It is possible to report a more detailed case history in connection with the second accident. It involved a smaller air-to-air missile with no airframe or internal resonances below 50 Hz, subject to 60g axial boost acceleration at the beginning of flight, 30g possible lateral maneuvering loads during any part of the flight, and a 5g swept-sine wave during vibration test, intended to simulate flight vibration, except at extreme low frequencies where the displacement amplitude was limited to 1/4 inch. The acceleration figures were used as fragility estimates for shipping container design.

An officially acceptable container design was achieved only with great difficulty, over a period of years. In the meantime, there was engineering chaos. A required 3 foot drop, and a fragility estimate of 30g acceleration for the missile determined the maximum resonance frequency and minimum sway space for the container. The primary difficulty came from comparison of the specified container vibration inputs with a 5g fragility estimate for the missile. This required extreme damping of the resonant suspension, which could be accomplished at that time only through friction dampers. These dampers, specially designed for each prototype, were bulky and potentially unreliable. This led to extremely bulky prototypes, which for some time the customer representatives refused to accept. However, there were no actual quantitative limits on bulk or gross weight to use in official tradeoffs. (There are now some limits on bulk for shipboard containers, based on dimensions of bulkhead doorways, etc.) The customer representatives showed no real sympathy toward relaxation of environmental requirements or raising of fragility estimates above the quoted legal figures in the environmental specifications for the contents.

At one time during this period, rough road tests and drop tests with an actual missile, complete except for warhead, in a rudimentary container, were carried out by the contractor in an effort to determine whether the design problem needed to be as difficult as it appeared.

The container for the special test was not an official prototype, but a simple plywood box with about 3/4 inch of foam rubber cushioning on interior wooden supports. It had been constructed for air transportation of the missile to the experimental firing range. It was felt that, if the missile survived a severe realistic test with only this rudimentary protection, the friction dampers in the prototypes would be proved unnecessary. The container was constrained loosely over the right rearmost axle of a flat-bed trailer truck, by a two-by-four wooden frame nailed to the truck bed to limit sliding, and by steel bands passing from the truck bed over the top of the cover.

A rough pot-hole dirt road was located. The truck driver was instructed to drive as fast as he could, back and forth, until he had accumulated 30 miles - a cumulative vibration environment judged to be well beyond any that would be likely in actual transportation.

The initial rough road test resulted in some loosening of wood screws from the container and some denting of the missile airframe. For subsequent repetition of this test, the area of cushion was increased to provide more uniform support along the missile axis. To provide, in addition, better axial restraint, a plywood flange was attached to the missile and, in turn, supported in foam rubber front and back. After repetition of the rough road test, no damage to the missile of any kind could be detected by inspection or system functional test. Since the friction dampers were related to the vibration rather than the shock environment, it was felt that these results by themselves justified omission of the dampers from the official container design.

However, the contractor proceeded further with drop tests, starting at 1 foot of height and proceeding to 3 feet. The box was oriented to impact on the bottom, with the missile axis horizontal. No damage or tendency to malfunction was discovered except for an intermittent after the 3-foot drop, although the cushion was obviously bottoming hard enough to produce peak accelerations well in excess of any fragility estimate. Although the resonance frequency and sway space were not the primary reasons for bulk in the prototype containers, it was felt that these results could be used, if desired, to justify an increase in resonance frequency and decrease in sway space.

Accelerometers on the missile had been avoided during these tests -- partly for simplicity and partly to avoid distraction from the simple question of whether the missile in a rudimentary container could survive extreme external environments.

However, the customer representatives rejected both test results as irrelevant, remarking that the only consideration of interest was whether the container met its specifications, subject to the fragility estimates for the missile.

Somehow, in time, a container design was officially accepted by the customer. Subsequently, a truckload of missiles in their containers fell over. A frantic inspection and functional test to determine whether anything was salvageable, failed to disclose any damage to the missiles.

During the discussion of this episode, the author raised the question whether it would make sense to reflect the specified external container environments through some standard internal suspension, selected so it would not be very difficult to engineer, and apply the responses as additional requirements on the missile itself as evidence of its transportability. This provoked a more humorous response than was anticipated. It was claimed that missiles are rugged enough now, except that their designers either do not know it or are not in a position to admit it. The additional requirement on missile design would cause worry, increase the missile weight and result in flight performance penalties. The only practical solution would be more devious -- give the missile designer the usual design and test goals, tell the packaging engineer the missile will be able to stand twice as much, and never let the two people (or engineering teams) communicate.

Comment

Accidents such as these, in which a missile survives an environment almost ridiculously extreme, are more likely to be remembered than those in which some damage is incurred. Yet, the two missile accidents support the report, in Section 2.1 of this chapter, of accidents during hardware manufacture, in suggesting that actual fragility may often correspond to much higher levels than the fragility estimates as now generally made.

In commenting on the longer case history, we will work generally backward from the climax in which the missiles survived an almost ridiculously severe accident, dealing first with some aspects of the final discussion, second with the significance of the accident, third with some administrative considerations, and fourth with an elementary technical analysis.

After completing his travel and participating in various meetings to gather information, the author does not agree that supplementary design requirements to ensure transportability of a small missile would necessarily result in excess weight and flight performance penalties. This would depend on the particular contractor and customer, and even on what portions of the two organizations became involved. The result would correlate, not with the purely technical competence of the engineers, but with the type of local organizational plan, the past history of inter-group cooperation, the kinds of rule of thumb already in use in design, the degree to which these are used erratically or systematically and consciously, and the way in which qualification specifications are written.

No example was found of converting specified container inputs to standard container outputs for supplementry missile requirements as proposed. This was, in fact, not an entirely serious proposal by the author but more a means for provoking discussion. However, in Section 2.1, some supplementary design requirements that tend to promote transportabiilty or ease of packaging have been reported.

The question of communication and negotiation between missile designer and packaging engineer on matters such as hard points did not come up in the discussion. The jesting suggestion that communication be avoided would most certainly not apply to such matters.

The troublesome friction dampers in the early prototype containers were required because of considerations of vibration. The spectacular accident that climaxed the case history was a shock environment. Any relation between the two is indirect. Nevertheless the accident does reinforce earlier inferences that friction dampers were not necessary.

Any quantitative comparison of the rough road environment with the vibration requirements of the specification would have undoubtedly involved sine-random equivalence -- a problem to which there is no general valid solution even now, after numerous analyses in the literature. The customer representatives who rejected the rough road test and drop test evidence on the transportability of the missile in a minimal container had little choice. They had no authority to do otherwise, had no one obvious to turn to who might grant such authority, were not and could not have been selected for insights into subtle matters of shock and vibration engineering, and if they had deviated from the strict legalities of the situation would have been extremely vulnerable to any challenge.

However, for readers who are at least familiar with the elementary concept of mechanical resonance -- or who take time to read Appendices 3 and 4 -- it is possible to show that the fragility estimates were actually overconservative, at least for vibration, and that extreme damping in the container was unnecessary. We can do this by extrapolating from either the static or the dynamic design and test requirements for a missile. The chosen suspension resonance frequency, between 10 and 15Hz and in the same range as the usual eventual choices for all small missiles was at most one-third of the first significant resonance frequency of either airframe or airborne equipment. Even if the suspension resonance was raised by a factor of 2, there would be little further amplification of any test vibration at this frequency by mechanical resonance within the missile. In addition, at all resonances of the missile, when excited at their own resonance frequencies rather than at the container frequency, the responses would be less if the container suspension was more lightly damped. But the damping decisions were determined by considerations only of excitation of the missile at the container resonance frequency, and a fragility estimate constant with frequency.

Let us first extrapolate from the 30g static acceleration design and test requirement, which, for reliability, must have been exceeded by some reasonable factor by the actual fragility of the missile in the static and low-frequency range. This was related primarily to tensile and compressive strengths. Proceeding from it to a suitable maximum permissible vibration peak level to avoid excessive fatigue is somewhat nebulous, depending on the material, but this maximum level should be some reasonable fraction -- say corresponding to 10g -- of the tensile strength. The drop test and accident results suggest that the tensile strengths may have corresponded to 60g or more, rather than 30g, so the 10g figure for fatigue would not appear very risky.

Now let us extrapolate from the 5g acceleration dynamic design and test requirement. Consider the first resonance within the missile. Since this was not an isolation resonance, there could have been no concerted effort to damp it. The vibration response must have been at least 10 times the input or at least 50g. Consequently, in the region of the container resonance, the parts involved in this missile resonance should have been able to stand 50g peak at the container resonance frequency.

Were the parts involved in the higher frequency resonances of the missile this rugged? We cannot give quite such a definite simple answer, but a more conservative estimate should be adequate for the container engineering problem. When excited by 5g at their resonance frequencies, their interaction, especially if they are close together in frequency, might result in more than 50g response. It is also possible that a higher frequency resonator might be isolated by a lower frequency resonator so that its response at its own resonance frequency might be less than 30g. But the same parts would probably have to withstand the full response acceleration at the lower resonance frequency. In any event, the equipment designer would not have had a comprehensive list of these resonances or a comprehensive analysis of their relationships. He would not have had either the incentive or the information to vary the ruggedness of parts closely in proportion to response in vibration test. So any parts that by any chance would be lightly stressed in vibration test may well have been as rugged as the rest. To claim they would all stand 50g peak at the container resonance frequency might involve some risk, but there should be little risk in a 10g claim. This number, if it could have been used as a fragility estimate, would have eliminated the need for friction dampers.

The suspension resonance, as in most missile containers, was chosen between 10 and 15 Hz. In consideration of the drop test and accident results, both involving hard bottoming, would doubling this have been likely to provide enough advantage to outweigh any risk of inadequate protection? This question was less critical than the damping to the size of that container, but it is worth considering, at least casually, on the assumption that the modification would not have left much of the missile cantilevered without support. The container was to be engineered to produce no more than 30g on the missile on a 3 foot test drop, with just enough sway space to prevent bottoming. But the 3 foot drop, while not an unreasonable test height, must have originated ultimately in a somewhat arbitrary decision. In actual transportation, there is no reason to believe a 3.5 ft. drop to have a negligible probability of occurrence by comparison with 3.0 or even 2.5 feet. From a stricly legal point of view, the drop test can be construed as allowing unlimited damage to every missile that encounters a drop, in its container, during transportation, of more than 3 feet. Especially in view of the report in Section 2.2 about the loading of airplane cargo, this apparent permissiveness may not be desirable. If the container resonance had been doubled without changing the sway space, the acceleration peak from a 3 foot fall would have increased to 60g, but bottoming would not occur up to a 6 foot drop. The extent of anticipated damage in mishandling would then have been crudely in inverse proportion to the probability of occurrence of each drop height rather than increasing abruptly after 3 feet.

However, the drop test and accident results indicate strongly that the missile could actually stand much more than 30g peak at low frequencies. Perhaps the sway space in the container suspension could have been reduced 25 percent or so with little risk, in conjunction with the increase in frequency, providing a suitable snubbing action was also a requirement in the container specification.

2.4 Commercial Versus Government Packaging

The cases just discussed suggest that the small missile may, up to the present, be one of the most difficult examples of current decision-making if its shipping container is to be designed expeditiously and is to provide protection proportionate to the need, within reasonable limits of bulk, reliability and cost. The small missile is precious enough to suggest a legally meticulous approach to the design of its container without being so expensive that extensive or careful data acquisition is approved.

Before passing to other examples of Government packaging that may in part reinforce this impression, it may be worth while to discuss, for contrast, the opposite extreme -- commercial packaging. This was not a subject of extensive investigation for the present report, but some visits were planned primarily for information about it and some unexpected insights were gained elsewhere. Commercial packaging differs from Government packaging in supplier-customer responsibilities, in legal aspects of any damage in shipment, in basic philosophy, and in technical approach. All aspects are closely interlocked and should be discussed together.

Whereas the term Government packaging, regardless of technical details, applies primarily to containers that, as well as their contents, are deliverable items explicitly mentioned in contracts, commercial packaging seldom involves any legal design requirements by contract or purchase order. If the container should be reusable or readily disposable, the supplier of the contents, rather than the customer, makes the decision. The transportation he must consider is normally by commercial carrier to the purchaser of the contents, and sometimes in the reverse direction (and return) for servicing or calibration. For any other transportation, the purchaser takes his own risks.

If the purchaser receives the merchandise in defective condition from the supplier, the latter will normally replace it. He, in turn, files a claim against the carrier, who usually pays the claim. This aspect of liability for damage in shipment is peculiarly commercial. It works out as it does in part because of a competitive market and in part because the purchaser, carrier and supplier are separate and distinct. Eventually, of course, in an indirect way, the purchaser or the general public pays the costs.

The details of immediate paper work and negotiations after damage of Government merchandise in a Government shipping container are different. If the customer and carrier are both part of the Government, no claim can be filed against the carrier. The contractor does not normally replace the damaged item, partly because he has no practical way of spreading such costs over a large number of customers. He obtains his business usually by competitive bidding in response to Government requests rather than by offering his product to a more general competitive market. This provides no mechanism whereby the contractor can collect from one branch of the Government the cost of defective merchandise encountered in another -- nor would this be desirable. The first official paper work after detection of damage is the filling out of a failure report -- a document whose first official impact could be to question the adequacy of design of the contents. If, however, the customer and contractor adhere to the commonly accepted policy that the contents should be designed only for the environmental conditions of use, the legal impact of the failure report is usually diverted to considerations of container design adequacy.

These contrasts are generally consistent with a difference in philosophy. In Government packaging, a container is usually expected to be completely adequate up to some specified level of environment, without damage to the contents or itself. In commercial packaging, there may be no official or generally accepted philosophy, beyond the recognition of a qualitative need for protection of the contents. The more sophisticated participants in or observers of the engineering problem look upon it as a tradeoff between cost of the packaging and the package design on the one hand and the likelihood and cost of damage to the contents on the other. One electronic instrument manufacturer reports frequent mishandling in shipment, perhaps on 20 to 30 percent of the shipments according to evidence from container condition or arrival, but less than 1 percent damage to contents.

As of the time of the survey, cost and material shortages were forcing an increasing application of commercial packaging to contents delivered to the Government, especially contents for ground mobile applications. This amounts to leaving the packaging to the discretion of the contractor. This is quite a controversial subject, but there is little to be gained by taking sides here. By the time of publication, much more insight will have been gained by experience than could be offered here now.

For commercial packaging, the engineering decision process or technical approach is informal, relatively simple, and primarily a matter of good design practices. It is more readily responsive to changing conditions such as scarcity or cost of particular materials.

Commercial packaging is less likely to be reusable than Government, except when it is to the advantage of the seller of the contents to provide for portability in use or for return for calibration or maintenance. Otherwise, cost, availability of materials or manufactured parts, and easy disposability tend to be the aspects considered most consciously in the design. Whether an item must be fire-retardant is seldom used as a consideration in choice of materials. Furthermore, commercial packaging is often adaptable to a variety of contents, through the use of filling that readily conforms to particular contours, foams cast or trimmed according to the shape of the particular contents, or adjustable supporting structure.

However, commercial containers are not necessarily inferior in quality for the intended purposes. Some are ingeniously designed, and some, with at most minor modification, would meet Government environmental specifications or come close to doing so.

An accident similar to the two missile accidents of Section 2.3 was reported. A well-designed multi-purpose commercial container was used in shipping some calibrated electronic instrumentation by truck. A count sometime after delivery disclosed several containers and contents were missing. A search along the route eventually located the containers in a ditch. The containers were damaged, but the contents were still undamaged and in calibration.

Comment

To summarize briefly the legal and design approaches, commercial packaging, like in-use isolation, is left to the discretion of the engineers most intimately concerned, whereas Government packaging is subject to contractual requirements. These requirements, in the absence of the incentive of a competitive market, tend to ensure some minimum level of quality of protection but make the decision-making process more ponderous -- often out of proportion to the practical advantage gained. There may also sometimes be an overemphasis on the capability of the container itself as opposed to the contents to withstand extreme mishandling without damage.

In the event of damage to contents, the traditions of liability and blame are less than ideal for either Government or Commercial shipping. In the former, the blame tends to be laid on the container designer. In the latter, the carrier usually assumes the liability, although he may refuse to ship some items to hold down his insurance rates. Both situations are examples of placing incentives where they may have the least benefit. The Government container may already have been forced by its specification requirements close to any acceptable limits on bulk, weight and cost, whereas a suitable redesign of the contents may not be technically difficult. The commercial container could be considered along with its contents for possible redesign, but carriers who assume liability do not have the authority for such redesign. Furthermore, they may be in a poor financial position to assume the liability, and having done so, in an even poorer position to make improvements in service.

2.5 Packaging of Space Hardware

Let us recall the missile "flight loads", namely the 30g quasi-static maneuvering acceleration, and the 5g swept-sine wave vibration test intended to ensure reliability under flight vibration, whose use was reported in Section 2.3 as a basis for establishing container design parameters for small missiles. One question asked by the author at various meetings was how we could establish practical design parameters for packaging a small space payload or similar space hardware by the same general approach. The boost accelerations during flight seldom exceed 6g, and there are no maneuvering accelerations to serve as a basis for fragility estimates.

For some time, this question produced nothing but complete consternation regardless of the mix of people at the meetings -- from entirely structural designers to entirely packaging engineers. It was, of course, an impossible question, capable of no direct answer. Eventually, at organizations actually involved in space hardware design, packaging and delivery, two ways of evading the question were offered.

The first solution was a complete evasion. The organization felt that it had sufficient control over the transportation conditions for the few units to be delivered so it could use an essentially commercial (specificationless) approach to packaging without any hazard of excessively severe environment. This appeared to be a successful practice, with no history of appreciable damage in shipment, and no indication of adverse criticism by anyone concerned.

The second solution involved additional empirical precautions reported and discussed already at some length in Section 2.1 -- a multiplying up of flight gust loads by weight dependent factors to provide initial assurance that the hardware could withstand vibration and shock test without major redesign, followed by the use of the corrected loads as points of departure for fragility estimates.

Comment

The question asked was an ultimate reduction to absurdity of an extreme decision process that is widely assumed to offer as a purely technical zero-risk approach to packaging, but can be in actuality a primarily legalistic practice that accepts numbers only from documents with an official legal status and excludes most technical insights. The practice attempts to make the risk of damage by transportation environments external to the container, up to but not beyond certain arbitrary levels, negligible by comparison with the normal engineering risks that the contents may be inadequately designed for its intended reliability and function. Simultaneously, the practice ignores the possibility, of overdesign of the container, with consequent penalties in weight, bulk, cost, schedule and engineering effort. If this can be interpreted as a system-engineering tradeoff, it is at best an unbalanced tradeoff. The fact that its most extreme form cannot be made to work satisfactorily for the most critical aerospace hardware transportation damage risks encountered by the Government suggests that it also can be beneficially modified when the damage risks are less critical.*

The author has maintained for some years that shock and vibration engineering is best accepted as a management and legal as well as technical function and would be made more effective by a concerted effort to optimize nontechnical as well as technical aspects. As a partial converse, the basic decision-making for packaging should not be allowed ever to be in actuality a purely legal matter to the detriment of good management and technical practices.

Several alternatives have been reported and commented on in this chapter. More will come later.

In these comments, there is no intent by the author to be caustic about environmental specifications in general or the people that write or apply them. Specifications are an essential and important feature of limited-source

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*Appendix 7

limited-customer procurement. Rather, the intent is to emphasize that there can sometimes be benefits from keeping the managerial, legal and technical aspects in better balance than tradition now permits. This is not an easy challenge, but recommendations are offered, especially in Chapter 5.

2.6 Other Government Packaging Practices

The procedures for initial decision-making for the Government shipping containers are actually more varied than the examples given so far -- even if only small guided missiles were to be considered. Practices vary with the type of contents, the intended use, the customer and even with the particular division of the contractor or customer organization.

For air-launched missiles, packaging is usually a responsibility of the contractor, subject to customer specification. For ship-launched missiles, packaging is usually a responsibility of the customer, but subject to generally similar specifications. For ground-launched missiles, the packaging design responsibility may go either way.

Section 2.3 reported a suggestion, half in jest, that the missile designer be given one set of flight environments or corresponding test conditions, the packaging engineer be given some larger numbers as fragility estimates, and communication between the two be prohibited. No instance of this exact procedure was discovered, but something like it can be reported in connection with some ship-launched missiles. The container is designed by the customer as part of logistics effort. Environment-fragility comparisons are confined to drop test considerations. For vibration, limits are placed on the transmission of the container in the neighborhood of the container resonance. The missile design team and the packaging team are so separated organizationally and geographically that there is no opportunity to discuss any apparent or implied inconsistency in vibration design objectives. No excessive transportation damage as a result of this procedure was reported.

On the other hand, the bypassing of the environmental-fragility comparison is not universal for ship-launched missiles. Some of the same design decision difficulties were reported as for the air-launched missile discussed extensively in Section 2.3 In addition, because of divergent traditions in different divisions of the same customer organization, practical problems were reported from one environmental specification being required for design and a different one for test.

For some ground-launched missiles, the vibration environment is virtually ignored in container specifications except for precautions to ensure, at least indirectly, against undamped internal supports. On the other hand, the strongest incentives for missile and container design to begin simultaneously, and for communication and negotiation between missile and container designers, on matters such as hard points and the best means of constraint within the container, were found in connection with ground-launched missiles.

Although the negotiations for environmental capabilities of containers for small missiles tend to be formal and legally meticulous, the same procedures are seldom followed for spare internal units, except when there is reason to consider them especially fragile. Packaging is left more to the discretion of the contractor, as in commercial packaging.

Spares and deliverable portions for large missiles may be another matter, often subject to the same packaging formalities as complete small missiles. One case was reported in which the official design accelerations for an ICBM liquid rocket engine were so low compared to the specified transportation environments that packaging according to the initial legal requirements was technically impossible. The problem was resolved only through extensive discussions, whereby it became clearer to the engine designers what sort of protection by a container was possible, and the engine and packaging engineers arrived at agreement on more realistic fragility estimates for the engines.

With both ICBM liquid rockets (swiveling for steering purposes) and scanning radar antennas, a problem of caging (immobilizing) for shipment was reported. The basic designs were completed before packaging was considered, so no provision for caging was incorporated into the hardware.

At another extreme, for complete ICBM first stages and large space boosters, the distinction between container and transporter disappears. Design decisions involve less legalistic formality but more intensive and sophisticated engineering effort. Modelling studies by computer are carried out for the transporter, much as in the design of an airframe, and instrumented trial runs or instrumented actual deliveries may be provided for. As with transportation of space hardware generally, precautions are taken to control the environment through monitoring and control of air spring pressures, speeds at railroad crossings, etc.

Packaging of devices containing nuclear materials is engineered in much the same way. In addition to any considerations of impairment of function there are hazards of radiation shield rupture and environmental contamination as a consequence of structural rupture. Therefore, the primary consideration is preservation of structural integrity.

On the average, Government packaging involves more considerations of safety than commercial packaging, because of the nature of the contents. Therefore, there is greater emphasis on use of fireproof or fire-retardant materials.

But the simplest approach is taken for the contents associated with the greatest potential risk -- conventional munitions. There is little or no contamination hazard, but the mechanism for initiating an intentional explosion, commonly involving no electrical circuitry, is simple, not conducive to versatility of internal safeguards against accidental detonation, and sensitive in principle to sufficiently severe environment. In particular, in a bulk shipment, any one explosion could lead in turn to a series of others. But packaging amounts to little or more than palletization in layers -- tight confinement in position, often by wooden pallets or separators. A few catastrophic accidents have occurred, and at least one remains under litigation. But it is not clear what caused the accidents, whether any practical or conceivable different approach to shock or vibration would have been more effective, or whether use of more or better fireproof partitions would have reduced or merely delayed the effects.

Comments

The relatively casual approach to packaging of spare internal units would undoubtedly be justified on the basis that damage to a spare unit is less consequential than damage to a complete missile ready for use. Note, however, that extreme formalism in packaging of an individual spare, especially with high drop test height for low gross weight, would lead to a container with more sway space than contents, and high cost per unit transported.

It may be fortuitously better for all persons concerned when initial legal packaging requirements are obviously absurd rather than merely technically difficult. This leads to communication, negotiation, application of technical insights and possible engineering tradeoffs, whereas otherwise the packaging engineers may be left with an extensive frustrating effort to accomplish an almost impossible task. But it would be better if, more generally, packaging design and contents design began simultaneously and the former were made to conform more to the general traditional pattern of subsystem design parameter definition, tradeoffs, and equalization of engineering risks. The aging problems provide further support for this point of view.

The large missile or space booster is expensive or precious enough so that extension of it structural design methods to the transporter is acceptable and has little effect on total cost. Generally, failure point fragility rather than mounting point can be used as the primary design criterion, thereby permitting a higher order of validity in the approach.

Compared to the spare internal unit or the large booster, the small guided missile is an awkward intermediate packaging challenge. It appears too costly and hazardous for informal packaging engineering. Yet, it is not precious enough to justify the more sophisticated approaches and more extensive and meticulous data gathering associated with ICBM booster transporter design or packaging of nuclear devices. Formal approaches that appear to be based on the best scientific principles show poor cost/effectiveness in the absence of precautions to ensure that the quality of data will be adequate to the challenge.

Conventional munitions, as exemplified by cannon shells, represent the extreme opposite case to the space payload for packaging purposes. For the latter, the official flight design environment is too mild for direct use as a packaging design criterion. For the former, the design environment is too severe for sensible use in quantitative packaging decisions. In addition, in the event of accidental explosion of one round, the enviroment imposed on neighboring rounds is potentially even more severe and less predictable. The two contents are also opposite in respect to quantity of production and cost per item or round.

2.7 Cushions Versus Isolation Frames

The purpose of this section is to contrast cushions of rubberized hair, foam rubber or foam plastic with frames or clamps supported by rubber shear mounts or other commercial or special point-to-point isolators.

The isolators, especially with silicone rubber, were felt to perform better than porous cushions at extreme temperatures. Temperature problems can arise from changes of material properties at extreme temperatures or from freezing of absorbed water. Sub-freezing temperatures are seldom encountered in the hold of a ship. On land, however, temperatures are less extreme for the continental United States than for general overseas transportation or storage.

There was some feeling that the temperature extremes called out for containers were sometimes more severe than warranted by anticipated use, thereby leading to more design effort and container cost than was really justifiable. There was a tendency to favor frame and isolator systems over cushions for missiles because of easier axial restraint.

Foam cushions were favored for electronic gear because of their lower cost. However, there was one consideration at least partially in favor of the opposite choice. The more frequently equipment must be handled without the protection of the container, the greater is the chance for damage. Therefore, there is an advantage in providing for any required inspection, maintenance, testing or calibration of the contents without complete removal from the container.

Comment

This last consideration is another reason why contents and container design should start simultaneously, with negotiation and information exchange between engineering teams.

2.8 Reusability

Reusability of a container is a more prominent consideration for Government than commerical packaging Internal supports for contents within a Government container are usually resonant isolators, partly for reusability after mishandling and partly because of the common official policy, that some vibration protection as well as shock protection is needed. There are, however, some porous plastic materials that recover slowly but almost completely after deformation, therefore potentially providing reusability along with shock protection, without either diminishing or amplifying the transportation vibration environment.

There was no quarrel with the basic idea of reusability, but there was some feeling that specifications could be unreasonable in requiring complete survival of container as well as contents after severe mishandling as exemplified by an extreme drop test.

Comment

Vibration protection for other than contents known to have some particularly fragile design feature is a tradition, not a scientifically demonstrated necessity. In much commerical shipping it is customary to immobilize any isolators that are built into the contents (as in phonograph turntables and record changers) rather than to provide additional or softer resonant cushioning for vibration protection.

The policy of complete survivability of containers after accidents deserves some tradeoff studies, dependent on the nature of the contents. Guided missiles, for example, in actual warfare and in some practice exercises, are expendable items. Therefore, there is some tendency toward generation of a large surplus of containers so as to counterbalance a possible small loss rate from accidents.

2.9 Specifications Versus Environmental Data

In most Government packaging negotiations, the environmental conditions considered for any environment-fragility*(referred to mounting points) comparisons are specification requirements, not actual data. When nuclear materials are to be transported, there is an opposite tendency -- to use data rather than specified environments. The latter approach was explained as utilizing data on representative transportation conditions together with independently estimated likelihood of occurrence of such conditions. Sandia Laboratories maintain a data bank for such applications. They publish an Index (SC-WD-66-142C) to this data bank. Further information can be obtained either from the Shock and Vibration Center or from Sandia directly.

Comments

Decision making from data rather than specifications requirements is potentially too cumbersome and costly for many applications.

It is the author's opinion that specified transportation environments should not necessarily simulate field conditions, and would be best justified on other grounds. For example, the cost of random vibration testing of containers to verify protection of contents would be difficult to justify. The merit of the specifications should be measured by the degree to which they lead to expeditious cost/effective decision making and the degree to which they provide motivation for design features that are adequate for the needs.

2.10 Uniformity of Suspension Parameters

Finally, in spite of the very cumbersome initial formal decisions process for design of the suspension or cushion within a container, it was the impression of the engineers interviewed that the designs eventually accepted by the

* Appendix 3

customers were very much alike in resonance frequency, damping and sway space. In other words, in practice the process serves as a costly, time-consuming way of arriving at basically standard designs.

CHAPTER 3

FINDINGS ON ISOLATION

Except for the properties of the ear, shock and vibration engineering is based on the same technology and the same background science as noise control engineering. But, whereas noise control engineering focuses entirely on control of the environment as necessary, shock and vibration engineering, under the influence of Government specifications, focuses almost entirely on the testing of hardware to unalterable environments and on redesign as failures or malfunctions are disclosed. The only common example, within shock and vibration engineering, of a conscious attempt to alter the environment in a beneficial way is the shock or vibration isolator. This is a system of damped springs, such as resilient rubber mounts, inserted between the mounting points of the hardware and the structure to which it is to be attached. The protective arrangement within a shipping container is also usually a resilient isolator. However, the subject of this chapter is shock and vibration isolation of equipment while in use, by isolators that are not part of any separably-deliverable item, except as spare parts.

The damped springs resonate* with the mass of the supported equipment at some low frequency. At frequencies sufficiently above this, the vibration and shock environments are attenuated if sufficient care has been taken in design. However, in the neighborhood of the resonance frequency, the shock and vibration motions are increased so that bottoming can occur, with consequent damage to the equipment, or consequent malfunction. As isolators require space, both for the added parts and for swaying motions, the decision whether to isolate is commonly made before the equipment is designed. The isolator if used may require maintenance and must appear in the spare parts inventory.

As environmental specifications have seldom dealt explicity with isolators for equipment as used, the concerned engineers on most projects have been left free by the customer to proceed according to whatever decisions they could negotiate among themselves, with perhaps some guidance from management or after-the-fact approval by the customer. While there were differences of point of view and practice, some simple patterns (or possibly non-patterns) emerged. The practices were almost entirely at variance with the impressions one would be likely to get from reading the existing technical literature. An individual engineer working on his assignments within his organization, and not responsible for a survey such as the author undertook, would have little incentive to publish his experience with such apparently unsophisticated matters, and in fact little opportunity to publish where it would be retained as a readily available part of the permanent record.

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The remainder of this chapter contains the reactions of the people interviewed to this general design problem, gathered under various appropriate headings, and followed by the author's comments and interpretations.

3.1 Response Computations

No evidence was discovered, in spite of numerous recommendations by theorists, for any systematic, wide-frequency range computation of response of isolation systems to shock or vibration as a significant factor in their design methodology. In particular, it was pointed out that, in a large fraction of the most important cases, structure design, equipment design, and design of any isolation system in between, must take place concurrently. In such cases no data can be obtained to support any but the simplest and most rudimentary response computations.

Comment

Response computation has been a traditional structural design approach--quite successful for static loads and excitations at the first few resonances when the excitations, dynamics and tensile strengths are reasonably clear.

For more complicated challenges such as wide-frequency range isolation systems, even if structure and equipment already exist, such computation is more difficult and less conclusive. Environmental test is cheaper, makes better use of readily available talent, can be equally valid, and can be a more reliable indicator of unanticipated failure modes. Response measurement can serve as an economical supplementary test, to guide equipment design, or for diagnostic purposes.

Response computation is not the only possible design approach. In the development of control system or servomechanism theory, emphasis shifted rapidly from computation of response of a proposed design to methods of rapid optimization. The methods in detail are too sophisticated for the problems under discussion here, and not really pertinent to isolation, except active isolation, which is considered only for very special situations. But it is not economical to use response computation approaches except for major structures that require or imply completion of a detailed design before modifications can be considered.

3.2 Mechanical Impedance

As an aid to the computation of response to shock and vibration, and as an indication of the influence of dynamic loading effects on response, many theorists have recommended measurement of mechanical impedance (the ratio of applied force to vibrational velocity generated at the same point) or its inverse, the mobility, at interfaces where equipment and structure or intervening isolators are joined.*

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Only four instances were discovered of the use of mechanical impedance or mobility as an aid to isolator selection or design. At least two involved independent laboratories or consultants and were not performed within the normal organizational framework of a contractor. One isolator was actually for a noise control problem rather than a shock and vibration problem. It involved the design of a tuned resonant mechanical absorber for fan vibration in a jet engine--to "absorb" the vibration on its way to the passenger compartment in the fuselage. A resonant absorber was used to immobilize a helicopter pilot seat at the blade vibration frequency. One difficulty quoted in the use of mechanical impedance was the low measurement accuracy and the tendency for large spreads of data for repetition of the same measurement.* No instance of the use of the G-5 report of the Society of Automotive Engineers, which advocates mechanical impedance measurement and use of matrix theory, was found.

In shock and vibration engineering, the measurement of transmissibility (the ratio of shock or vibration motion applied at one point to the motion produced at another point) is quite common. One instance was reported where impedance concepts made possible the indirect measurement of transmissibility. The input points were not readily separable from the structure to which they were mounted, for excitation in the normal manner, but force gages could be incorporated into the junctions. Consequently, excitation was applied to an output point of interest. Force as a function of frequency was measured at both locations. On the assumption of linearity, the force ratio was taken to be the inverse of the acceleration ratio or transmissibility as normally measured.

Comment

The literature on mechanical impedance and mobility has concentrated primarily on computation of shock and vibration response versus frequency as opposed to identification of resonance frequencies. This would make extreme demands on accuracy and precision of measurement, especially when impedance curves are jagged. Furthermore, since wide frequency range response computation is not a common practical objective, mechanical impedance can seldom be used as a means for accomplishing it. However, deliberately qualitative or relative measurement, using a single type of instrumentation so as to decrease relative errors, with emphasis on critical frequencies rather than on magnitude, may eventually find its place as an aid in such design problems as optimum choice for isolator attachment points, as discussed later in Section 4.2 of Chapter 4.

Isolation of equipment as used is usually an interdepartmental problem. So is any associated mechanical impedance measurement program. If a consultant is called in, the problem is already recognized to have some special importance and therefore priority. The consultant is not necessarily bound by the existing organizational barriers. Although he does not have the responsibility for final engineering decisions, he has some freedom to gather the entire problem under

*Appendix 5

his own control for investigation purposes and to use the relatively efficient, small-team investigation approaches of a research laboratory.

In isolation problems, whatever sophisticated analyses may be undertaken can usually be accomplished in terms of modelling of the overall system without focusing explicitly on mechanical impedance at interfaces, except perhaps for an experimental check on the accuracy of modelling. But the operation of a resonant absorber is so intimately connected with mechanical impedance relationships, over a very restricted frequency range, that it is difficult to imagine an effective design approach without their use.

3.3 Fragility

The fragility concept was discussed before in the introductory portion of Chapter 2.

The prevailing opinion of the people interviewed in the survey was that fragility measurement, or estimation, as now performed, is impractical, whether used as a design factor for equipment isolation or for suspensions in shipping containers. A few engineers insisted that design of isolators could not be logical without quantitative fragility. The bulk of the engineering decisions for isolators appeared to be made without using the concept in a quantitative manner. No standard approach for determining fragility was evident or recommended. Often, the requirements of an environmental test (qualification test) that an item of equipment has passed are taken to be literally its fragility--purely for decision-making and satisfying contractual or other formal requirements but not for design. There have been a few attempts to measure fragility by test to failure.*

In some instances some particular part in the equipment to be considered for isolation is known to be particulary sensitive in respect to performance degradation (e.g. gyroscope drift or electronic noise) or, less commonly, reliability. In such instances, this becomes the controlling factor in the design decisions.

Comments

Quantitative use of fragility for isolation system design is usually optional. For shipping container design, its use by the concerned engineers is often a formal requirement. This subject has been discussed at greater length in the previous chapter.

3.4 Sine-Random Equivalence

According to those interviewed, use of qualification test requirements as indicators of fragility becomes more difficult when the prescribed vibration test was a swept sine wave but the apparently more severe vibration environment

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of the new application is random. Equivalence between the two is a very common problem to which there is no good solution. The approaches in use are arbitary and varied.

At one contractor facility, an equivalent sine sweep for a new random environment is obtained by computing the responses of a simple Q = 10 resonator tuned successively to center frequencies standard for third octave filter sets. The rms responses are multiplied by 3 and compared with the peak values originally specified for the qualification test. The decision to isolate or not is based entirely on this comparison.

At another contractor facility, the procedure is similar, but 10 Hz filters are used instead of the Q = 10 resonator and the rms outputs are compared with rms values for the qualification sine sweep.

At still another contractor facility, it was stated that the engineers never used sine--random equivalence as a basis for engineering decisions--only to satisfy legal requirements when everyone agrees the off-shelf equipment will survive and operate on the airplane.

Comment

If these procedures seem crude and horribly in need of refinement, the reader should consider, at this point, that commonly only one accelerometer may be allotted to define the environment for an entire equipment rack in an airplane, or perhaps one per shelf. There is a real question how much the refinement of the procedure should exceed the refinement of the data to be used. The question of how much data engineers should expect or demand will be deferred to Chapter 5, where a partial answer will be given.

The two procedures quoted were undoubtedly based on formulas for equivalence between random vibration and a fixed-frequency sinusoid rather than a swept sine wave. Most procedures for equivalence were established before it occurred to anyone to allow for the relatively small time the swept sine significantly excites any one resonance. The need for such procedures was much more urgent in the early years when random vibration test systems were rarely available.

The two procedures imply quite different assumptions about typical damping of resonators in the test item. The constant fractional bandwidth approach is probably the better.

3.5 The Decision Whether to Isolate

The previous topics, of course, bear on this problem and the associated methodology, but there are some supplementary aspects and engineering attitudes to report.

At one missile contractor facility, it was stated flatly that decisions to isolate are made out of panic, not logic. The design team inspects a new environmental condition and, out of fear, insists on isolation.

At another facility, the approaches quoted had more rationale and more the character of a management procedure if not logical technical procedure. The first approach quoted was to requalify an off-shelf item of equipment to the new environment. If the item failed, it would be redesigned or isolated. The alternate approach, if failure in the new environment appeared likely, was to isolate in order to save the expense of test for requalification.

A further strong opinion was that isolation was usually undertaken to prevent performance deterioration rather than reliability type failures.* It was also stated that environmental specifications tend to be overconservative and too severe for performance degradation tests.

Comment

Funding and schedule are important constraints on isolation methodology, which cannot be permitted to consume more than its share of either. On the other hand, some orderly, at least partially standardized, methodology for decision making is desirable.

Reliability type failures imply a fundamental nonlinearity--a threshold of environmental severity or time of exposure, or both, above which a disastrous effect can occur. Performance degradation has a more linear relationship to its cause. For reliability type failures, some safety margin or added severity built into the environmental test condition is desirable in principle, for testing a few times to the exact condition of the application, if known, would not prove that there is any safety margin in the design. The threshold of failure might not be exceeded except for the most obvious design deficiencies. In practice, because of enveloping of spectra or related procedures, specifications usually do reflect an added severity, but the amount is difficult to estimate. Requiring in-use quality of performance, as opposed to high reliability, for a test environment somewhat in excess of that of the application may on occasion lead to costly overdesign or unnecessary isolation. There are easier ways to strengthen a part to improve its reliability, once the weak part is identified, than to improve the drift rate of an inertial guidance gyroscope.

3.6 Effectiveness of Isolation

The prevailing reaction appeared to be that isolators are ineffective and undesirable. They take up space, may bottom and thereby intensify an excitation, may loosen or come apart, and constitute extra items for maintenance and spare parts inventory. However, the effectiveness depends on the particular technical problem and the kind of teamwork applied.

At one missile development facility, poor success was reported with isolation of complete units such as guidance units, but good success with isolation of individual parts such as quartz crystals used as frequency standards. The

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poor results were attributed in part to testing the isolation system on a shaker rather than on the actual structure, and in part to mechanical flanking paths (cabling and plumbing) around the isolator. It was stated flatly that mechanical impedance measurements would not help. But, apparently, in most cases, the decision to isolate turned out to be unnecessary.

At another location, it was claimed that flanking paths do not interfere with isolation provided sufficient money can be spent.

One contractor reported good success with isolation of individual relays--relays that need isolation above 100 Hz to avoid malfunction.

At another contractor location, the experience and practice were almost diametrically opposite to the first. Individual gyroscopes and accelerometers were never isolated. But good success was reported in isolation of complete inertial platforms for ships, provided they were to be used only for navigation, not fire control. Otherwise a compromise could be effected by using frangible pins as intentional flanking paths for motions normally to be measured. The platform would survive a direct hit on the ship and retain its navigation capability. The fire control capability could be restored shortly by replacing the pins.

It appeared that engineers are seldom given much latitude to redesign structure or equipment to make isolation more effective. But sometimes this is permissible--at least to the extent of relocating isolators at better positions. Sometimes some stiffening near the isolators is allowed. At one facility, shock and vibration was reported to focus in a structures group reporting directly to the chief engineer, so that interdepartmental disputes could be "kicked upstairs."

In space applications, one difficulty reported was a deterioration of rubber in hard vacuum.

Sometimes high-intensity noise testing is required for missile airborne equipment intended to be mounted on mechanical isolators as a check on a possible acoustic flanking path.

Comment

It appears that mechanical flanking paths were more important for the missile equipment than the shipboard inertial platform. Mechanical impedance measurements are difficult to carry out as an interdepartmental project and have no value unless they are allowed to affect the design. Modelling techniques or simple intuitive redesign would probably be a more effective means of dealing with flanking paths.

A quartz crystal is an ideal example of something that is easy to isolate, especially if quality of performance is the primary criterion. Its operating frequency is usually in the megaHz range or higher, so that an effective isolator can be stiff by most standards. As the crystal consumes negligible power and requires only the lightest of wiring (one wire in, or wire out), mechanical flanking paths are not a serious problem.

Precision performance of an inertial platform is critically dependent on the alignment of its gyroscopes and accelerometers. Consequently, they cannot be individually isolated. Fire control is critically dependent on the measurement of the orientation of an inertial platform with respect to the ship, whereas navigation is less so.

There can be an acoustic flanking path around an isolation system, although it is not usually important unless the isolated equipment has large exposed areas that are light and flexible. There are problems in devising realistic high-intensity noise tests--the mechanical mounting for the test item must be realistic, and the response is not uniquely related to sound pressure level. The type of sound field and its orientation with respect to the test item can also have an effect. Nevertheless, in some instances high-intensity noise testing of airborne equipment, especially if it is to be mechanically isolated, can be an effective tool in guiding design.

3.7 Frequency as a Design Criterion

Sometimes isolation systems are designed primarily out of consideration for frequency range of excitation rather than level of excitation. At one contractor facility, it was reported that the program manager on occasion issued instructions to proceed in this manner. It was not specifically stated, but there was a general implication that isolation systems designed in this way were above average in performance. At one contractor facility it was stated that successful design of an isolation system solely on the basis of environmental specifications was impossible. It was necessary to consider the actual environment. The specifications were of concern primarily in respect to meeting formal contractual requirements after completion of isolator design.

At several meeting locations, a hole in the spectrum of excitation of airborne equipment by jet aircraft, suitable for the major resonance frequencies of isolation systems, was reported. At one facility it was said to center around 30 to 40 Hz. At another it was described as lying between the major structural resonances of the airframe and the high-frequency aerodynamic excitation.

In contrast, helicopters and propeller driven aircraft were reported to have a high concentration of energy in the 50 and 60 Hz range, requiring 6 to 10 Hz highly damped ($Q = 1.5$ to 3) nonlinear isolators if any were to be used.

One contractor reported a situation such that the qualification test, possibly inadvertently but usefully, results in the placement of isolation resonances in a rather narrow spectral hole. It was claimed that the usual shipboard vibration environment does not extend above 33 Hz. The medium weight shock test machine for shipboard equipment was reported to have a first resonance at about 60 Hz. Consequently, isolation systems were being designed to resonate about half way between. This was claimed to be, somewhat fortuitously, a good method for helping equipment to withstand a near miss environment--except for sophisticated electronic equipment, which became very costly. But this appeared to be more of a reservation concerning the cost of designing the equipment for an extreme environment than an adverse comment on the isolation systems.

A large transport airplane was reported to have a landing shock concentrated at 100 Hz. Another facility acknowledged this but did not consider the shock to be severe for on-board equipment or cargo.

It was pointed out that a terrain following airplane, say at 100 ft. or so above ground, suffers a strong low-frequency excitation that is incompatible with low-frequency isolators.

For some ICBMs the vicinity of 30 Hz was strongly recommended for isolation system resonances.

Comment

For general simplicity, environmental test specifications focus primarily on level of excitation, with frequency range a secondary consideration. Further confounding the problem of isolation system design, the levels are usually unrealistic at the low-frequency end. There are several possible remedies without complicating the specification requirements.

For example, the specification writer can require that estimates of the actual environment, especially in respect to frequency range, also be considered in the design or selection of isolation systems. Further, he can require that waivers be requested as necessary to make isolation systems compatible with the actual environment.

An additional variation would be for the specification writer to supplement test (and design) requirements with estimates of the anticipated environment, or with data if any exist. Such supplement must be carefully worded, preferably with an explicit disclaimer, so that they will be acceptable as tentative information rather than as legally binding instructions. The contractor should be expected to use the information at his discretion and to explain or justify such use.

3.8 An Isolator As A Damper

A space telescope was designed as three sections with isolators in between, partly to make the modes of the different sections independent in frequency, partly to damp the modes, and partly to isolate, in an end section, a Vidicon tube that tended to be microphonic.

Comment

This design effort is significant, for attention to resonance frequencies as design considerations, for attention to damping of modes, and for a novel and ingenious method of damping. Both resonance frequency control and resonance damping deserve more emphasis in equipment design generally. Furthermore, damping deserves more emphasis in design of fixtures for vibration test and shock test.

CHAPTER 4

OVERALL EVALUATIONS AND RECOMMENDATIONS FOR ISOLATION AND PACKAGING

Chapters 2 and 3 reveal a picture of engineers trapped in methodologies in which they have little faith and stifled by a formalism that leaves them little incentive to look for alternatives -- engineers at sea in a world of interdepartmental and interorganizational negotiations. Isolation and packaging, at least, have become a crossroads for legal and quasi-scientific thought, with little or no management attention, either to provide beneficial guidance or to measure the effectiveness of approach. The author uses the word quasi-scientific because the negotiators have been forced to maintain an appearance of being scientific while suitable supporting data are denied and creativity to make the best of the situation is crushed. Please note that these harsh comments are intended as a criticism, not of any of the people involved at the management level or below, in either customer or contractor organizations, but of a traditional approach in which all have been obliged to perform and which is only now maturing to a point such that introspection has a chance of improving it. Chapter 5 will show that this applies more broadly, reveal some of the reasons for it and suggest some changes of viewpoint. The present chapter will limit itself primarily to exploring and recommending specific alternatives for isolation engineering and packaging engineering, together with the specifications that exert direct or indirect control.

4.1 Recommendations for Isolation Engineering

Contrary to possible appearances, the state of the art of in-use isolation engineering, as reported in Chapter 3, is not in a major chaotic crisis of technology, or in urgent need of a radical new technical approach or large dose of higher sophistication. If it often falters and results in isolators that are unnecessary or do not isolate as intended, or both, it seldom consumes more effort than it is worth. In fact, it would be inappropriate to lavish much more expertise on isolation than on development of the item considered for isolation. When the technology of shock and vibration more generally is improved, perhaps following some of the recommendations of Chapter 5, the technology of isolation will improve also, but isolation may then be resorted to less frequently.

In the meantime, however, isolation suffers from definite deficiencies of good engineering practice and good technical management. Accordingly, the following recommendations are made:

1. Require that, in decisions whether to isolate and in design of isolation systems, emphasis on critical frequencies be increased and that emphasis on formally-specified qualification vibration levels at low frequencies be decreased. More specifically, require that

a. The first frequency (or preferably the first three frequencies) of mechanical resonance of the item to be isolated, regardless of where in the housing or interior they occur, be known and considered in the design of the isolation resonance.*

b. The frequencies of the supporting structure (airframe, deck, etc.) mechanical resonances in the neighborhood of the anticipated isolation resonance frequency be known and considered in the design of the isolation resonance.

c. The frequency of any hazardous periodic excitation (propellor-tip passage frequency, combustion instability frequency, etc.) in the region of the anticipated isolation resonance frequency be known or estimated and be considered in the design of the isolation resonance.

2. Require that effectiveness of isolation be measured with a section of supporting structure, or simulated structure between the shaker and the isolation system, and with any plumbing or cabling in position that might affect the result. This should preferably be done in advance of final design, or design approval, with simulated hardware if necessary, but in any event, with resonance characteristics similar to those affecting an actual installation. This requires some engineering judgment as to how much of the supporting structure to include in the measurement. Above the isolation resonance frequency, the vibration level for this test need not correspond to any specified qualification level -- any convenient level should be adequate. In the neighborhood of the isolation resonance frequency, vibration levels should be so chosen as to exhibit any important effects of nonlinearity in the isolation system. The criterion of effectiveness is to be a curve of isolator transmission versus frequency -- the ratio of motion at the output of the isolation system to the equipment to the motion of the same equipment mounting points with the equipment hard-mounted to the structure, for the same motion of the shaker or fixture. This curve is to be enveloped for use in accordance with Recommendation 3a. In addition, a structural loading curve, with the isolator <u>input</u> motion in the numerator, is to be measured and enveloped for application in accordance with Recommendation 3b.

3. For equipment to be isolated during use, <u>permit or require departures from the vibration qualification specification</u>, according to a choice between two options, <u>of which the first is preferred</u>:

a. Test the equipment directly on the shaker or intervening fixture <u>without</u> the isolation system and without any cabling or plumbing except as may be necessary to permit monitoring of performance. Require that a test spectrum be proposed and approved that represents the <u>qualification spectrum modified according to an upper envelope of both</u> the transmission curve measured according to Recommendation 2 and a transmission

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curve measured with isolation system attached directly to the shaker or to an intervening fixture of essentially conventional design, as necessary, without any simulated structure. Permit waivers or deviations when failures in test can be shown to be due to this method of enveloping and not related to the environment of actual use of the equipment.

b. Test the equipment mounted to the shaker or fixture by the isolation system and with any cabling or plumbing attached to the equipment and to the shaker or fixture as realistically as possible. For the region of the isolation resonance frequency, if the qualification test levels would unnecessarily bottom the isolator, require that more realistic levels be proposed and approved, according to the anticipated application of the equipment. For higher frequencies, require that the qualification levels be modified in accordance with an upper envelope of the structural loading curve measured according to Recommendation 2. Consider waivers or deviations when failures in test can be shown to be due to the method of enveloping and not related to the environment of actual use of the equipment.

4. Apply the shock test through the isolation system and as stated in the qualification specification unless a modification analogous to those of Recommendation 3 can be devised so as to provide a more beneficial realism.

5. Require that any special environments, such as landing of an aircraft, that might cause bottoming of the isolation system, if not adequately covered by the qualification specification, be estimated and be provided for by adequate sway space or by snubbing.

6. Consider a deviation or waiver when knowledge of mechanical resonance, obtained in accordance with Recommendation 1, can be made to show that a test failure resulted from excessive excitation in some frequency band.

7. Preparatory to consideration of waivers or deviations, differentiate test failures as reliability failures which properly require some margin of safety, and performance degradations, which do not. Utilize advance differentiation of any anticipated failures as a factor in intial design of isolation systems.

8. Require a formal record of degree of success of isolation systems designed and tested, together with reasons for any deficiencies, and require that these be available for guidance of future isolation design decisions.

9. If the test specification, for simplicity, does not recognize that vibration and shock can be three-dimensional, and rotational as well as translational, require that all six modes of isolation resonance be considered and that evidence of satisfactory design with respect to all modes be provided.

10. Require that isolation systems that prove ineffective and unnecessary be eliminated from equipment designs so they will not require maintenance and need not be carried in the spare parts inventory. Where possible, redesign

of the equipment mounting points should be carried out in such a way that parts such as bushings are not added to take the place of isolators.

Recommendation 1 and expansions of the concept in later recommendations would permit using vibration qualification conditions and shock qualification conditions more or less as they are now written, but would imply a fundamental shift in interpretation and legal impact. For simplicity, shock and vibration qualification conditions are prescribed in terms of levels with little regard for realistic variation with frequency, and this practice would continue. But such requirements as now enforced by customer representatives and applied by shock and vibration engineers tend to suppress equipment and structural resonance frequencies* and other critical frequencies almost completely as factors in the design process -- or at least in the formal defense of design adequacy. The opposite approach, of design by critical frequencies alone, with little or no attention to level of shock or vibration response, is capable of better results, but a blend of the two approaches, as outlined here, represents a still better compromise. This recommendation is intended to decrease restraint on the use of the intelligence and technical training of the shock and vibration engineer. The proposed decrease of emphasis on low frequency vibration levels is clarified further in Recommendation 3b. The concept of using resonance frequencies in design will be expanded on in Section 5.2.

Recommendation 2 is intended to reflect into the formal demonstration of design adequacy any adverse interactions with the supporting structure and any mechanical flanking paths for vibration or shock, such as plumbing or cabling. In special situations, it may be necessary to go further and consider the acoustic flanking path past the isolator by the high level of noise inside the supporting structure.

In Recommendation 3, in order to avoid excessive dependence on engineering judgment as to how much supporting structure should be present or be simulated, the conventional practice of qualification without such structure is continued, and in Recommendation 3a is that a maximax enveloping is prescribed. The disadvantage of Recommendation 3b is that it is difficult to fasten cables and plumbing realistically when none of the actual supporting structure is present or simulated. Both 3a and 3b take into consideration the possibility that the actual structural motion may increase if the hard mount is replaced by an isolation system, in a way that provides a deterrent to over-optimism on the part of the design team, and in as realistic a way as is feasible when a standard qualification specification is to be a fundamental basis for initial design or for environmental test. If eventually definitive vibration data with the isolation system in use become available, these may serve as a basis for a more refined qualification condition, without the enveloping of Recommendation 2 to avoid overconservatism.

In connection with Recommendation 4, it would indeed be beneficial in principle to devise qualification modifications analogous to those of Recommendation 3, but shock testing is much less standardized than vibration testing. For the

*Appendix 4

Navy approach of specifying a test machine rather than an environment, modification would be inadvisable. For such reasons, it is best at this time to leave this matter for resolution according to the particular test approach utilized.

In any event, Recommendation 3 is an attempt to recognize that, for low frequencies, because sway space to prevent bottoming of an isolator is a critical design factor, the formal qualification requirements need special attention and a focus on realism for each particular application, beyond what is necessary or justifiable when equipment is used without isolation. Usually at these frequencies any equipment resonance that is not associated with isolation will be made to bottom and chatter by the vibration condition of any typical qualification specification, which will lead quickly to beneficial redesign such that there is no longer an equipment resonance in that range. Consequently the exact low frequency vibration test level is not a critical factor for hard mounts. In addition, Recommendation 3 is an attempt to recognize that at higher frequencies the formal qualification levels for isolated equipment needs special attention for a different reason -- application of standard vibration conditions without the suggested modifications is likely to provide an over-optimistic view of the performance of the isolator.

Recommendation 5 is a reinforcement of the idea that the formal design and test requirements for an isolation system need special attention at low frequencies, with a focus on realistic design for the particular application, so that design is adequate to prevent bottoming in use but more sway space than necessary is not demanded. Especially if an isolation system is not tested along with the equipment, <u>it should receive a separate review for design adequacy</u>. Whatever formal requirements are applicable should encourage and not stand in the way of good design.

The remaining recommendations reinforce a demand for improved technical management and improved engineering practice.

For such recommendations to have reliable impact on technical management, the actions of customer representatives, and engineering practice, they must be incorporated into customer and contractor qualification specifications. The intent here is not to provide a final wording and dispose of the isolation problem once and for all, but to indicate what generally could be accomplished without a radically different technical approach.

Furthermore, the recommendations represent compromises in recognition of the need for simplicity in design and test approaches, together with "safety valves" when the compromises result in unnecessary development problems. In other words, waivers and deviations are recognized as integral parts of the procedure, and guidance is given as to when these should be requested and when granting them should be considered favorably. Up to now, there has been no explicit management (customer or contractor) policy on waivers or deviations, which leads at one extreme to their abuse and at the other extreme to unnecessary horror on the part of the customer when it is found that specifications were not strictly complied with.

On occasion, it may be appropriate for an isolation system to be <u>identified as needing much more than routine engineering attention</u>, because of optical alignment requirements or similar considerations. The recommendations are not intended to stand in the way of application of whatever engineering expertise may be appropriate in such situations.

Finally, it should be noted that isolation systems that are shipped integrally with supported hardware may cause trouble in shipping, as evidenced by the commercial practice of inactivating them. For the remaining sections of this chapter, it will be assumed that any isolators present during shipment are inactivated in one way or another, unless satisfactory evidence is offered that this is unnecessary.

For the most part, these recommendations should be incorporated into specifications as guides to contractor engineering rather than as sufficient conditions for design acceptability. The customer should avoid taking the responsibility for the contractor's engineering decisions.

4.2 Role of Mechanical Impedance

In Section 3.2 of Chapter 3, it was reported that measurements of mechanical impedance* (ratio of applied force to induced vibration velocity, as a function of frequency) or mobility (ratio of velocity to force) are almost never used in isolation system design, and some reasons for this were offered. However, with some change of emphasis, mechanical impedance and mobility can be made into useful tools for the implementation of Recommendation 1 of Section 4.1. The virtue of impedance concepts, for this purpose, is that they permit a more fundamental view of the phenomena of mechanical resonance and mode shapes than can be obtained simply by putting devices on a shaker and observing maxima of response versus frequency.

Impedance concepts originated in electric circuit theory, as a means of predicting the interactions of two or more circuits when connected together, by means of measurements at the connection points while the circuits are still separate, without necessarily needing to know the interior details of the circuits. They have been carried over into mechanical systems as a means of predicting the loading of one mechanical device carrying vibration or shock motions, by another which is to be attached, by means of measurements at the interfaces before attachment, without necessarily needing to know the interior details of the devices.

The fact that changes of dynamical loading may be important in isolator design and test was recognized in Recommendations 2 and 3, without explicit reference to mobility or mechanical impedance, and with minimal complication of the design and test procedures. If impedance concepts could be utilized without excessive complication, they could be a powerful tool in the design of isolation systems and even of equipment more generally.

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However, most proposals to utilize such concepts in isolator design decision-making have assumed that, while the isolator design has not yet been carried out, the two devices between which the isolator may be inserted (equipment and supporting structure) exist so that measurements at the interfaces can be made, assume that reliable estimates of fragility of the equipment to vibration and shock referred to the mounting points (interface) have in fact been made, and focus on the computation of response magnitude versus frequency at this interface with and without a proposed isolation system so that comparisons to the fragility estimates can be used as measures of the need and adequacy of isolator design. Sometimes the hardware is available as assumed, but often it is not. When it is not, it was pointed out in Section 3.1 of Chapter 3 that the design of structure, equipment and isolator if any must usually proceed concurrently -- the decision whether to isolate must be made at the beginning and design must proceed before meticulous impedance or mobility data can be measured. On the other hand, if the structure and equipment already exist, Section 2.1 of Chapter 2 suggests that any fragility estimates available would be too unreliable for the present to justify response computation as proposed. Yet, the impedance or mobility measurements, if made, require the utmost precision of instrumentation and the utmost skill in its use.

Clearly, the emphasis on mechanical impedance or mobility must be changed so that existence of final design hardware is not necessary, measurements need not be so meticulous, and the data can be used to guide concurrent design rather than merely be reserved for design evaluation at the end.* In this, a cue can be taken from the control system designer or servo system designer. He does not carry out a final design of control system and make response computations to determine whether it is stable. Rather, he roughs out a tentative design and estimates its resonance frequencies and corresponding decay (or growth) rates, which, taken together, are known as the poles of his initial system and reveal its degree of stability or instability. Then he modifies his design so that the poles shift toward final values that are acceptable for the application. Finally, he may test the design or if necessary compute responses to ensure that no critical factors in the design or its use have been overlooked.

This suggests that mechanical design of equipment and any associated isolation system, for resistance to shock and vibration, can be made quicker and more effective by measurement of resonance frequencies, and secondarily associated damping, as design proceeds, considering their relationships, and making design changes to shift them. Frequencies that are close are usually unfavorable. High damping is usually but not always favorable. To the precision required, frequencies of resonance are easier to measure than magnitudes of response to vibration or shock, or mechanical impedance so that response computations can be made. Moderate shifts of resonance frequency are not difficult even when a design is not already committed and may bring dramatic improvements in reliability without significant weight or cost penalities.

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It would be to the advantage of customer, contractor management and practising engineer if qualification specifications were so written that attention to resonance frequency relationships during development for reliability would be encouraged and reporting on this would be permitted and in fact required as additional evidence of design adequacy of isolation systems and even more equipment generally. If this were so, mechanical impedance techniques could be made helpful, with minor complication.*

Consider, for example, the problem of determining resonance frequencies and mode shapes on supporting structure that is too large to be mounted on a shaker or might not respond realistically if so attached. If this structure were excited by a small shaker with a coupling such that both the applied force and the resulting motion could be measured, the ratio of these as a function of frequency, whether reduced to numbers or simply observed by comparisons on an oscilloscope, would be an indicator of resonance and to a first approximation independent to the specific dynamical properties of the small shaker. At nodal points (small motion) the ratio of force to motion would pass through a maximum, with rapid phase shift, as the excitation frequency is swept through a resonance. At antinodal points (large motion) the ratio would pass through a minimum, with rapid phase shift. Alternately, a ratio to motion measured at other points than the point of excitation by the shaker would permit tracing out mode shapes in a convenient manner, in terms of transfer impedance. Usually, coincidence of a structural resonance frequency with a resonance frequency of the equipment or equipment plus isolation system is an unfavorable situation, and mounting near an antinode of the structure is unfavorable. It should be recognized that a decision to isolate without allowing for the possibility of small design changes in equipment and supporting structure is not a matter of good technical management.

To return to the apparently simpler procedure of mounting an equipment on a shaker and observing resonance in terms of the ratio of response motion to motion at the mounting points, or in other words in terms of transmissibility rather than impedance or transfer impedance, yields frequencies that are characteristic of the equipment as mounted to something much more massive and rigid. On the other hand, mechanical resonances observed in terms of a ratio to force at the mounting points would yield frequencies that are characteristic of the equipment as mounted to something much less massive and rigid, such as an isolation system.

While this emphasis on frequency rather than level would of itself make the measurement and utilization of mobility or impedance less difficult, it will be beneficial if any measurements on equipment, isolator or structure or any combination of them be performed by a single team, with no more engineers or technicians directly involved than necessary.

Finally, this emphasis on frequency in the course of development would make it easier to carry out meaningful computations of response whenever these

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prove to be useful, and would make it easier to obtain meaningful estimates of fragility whenever these prove to be useful.

4.3 Options for Packaging Engineering

Except for the possibility of using crushable cushions, packaging for shipment presents the same dynamical problem as isolation -- allowing the support adapter to resonate* in a controlled manner in a frequency range in which the supported equipment has no resonances or excitation of any mechanical resonances can be suppressed by choice of support points, in order to gain isolation at other frequencies where the equipment is more vulnerable and the environment would otherwise be a menacing factor. This definition is adequate for most situations.

The previous sections of this chapter, together with the underlying findings and interpretations of Chapter 3, have shown that isolation engineering has suffered from too little attention in environmental specifications to the special needs of isolators. It will be shown that packaging engineering has suffered from too much attention of the wrong kind.

The impact of environmental specifications as written has been to focus engineering effort on an artificially difficult decision concerning support resonance and sway space, to such an extent that not only the subtle considerations that appeal to theoreticians, but the very practical actions to avoid cantilevering a missile in its container, or to support it at "hard points", or to support it so lowest airframe resonances are not excited, are often neglected in new designs. The decision is artificially difficult because the specifications require what purports to be a rigorously scientific approach without ensuring that the supporting data will have sufficient accuracy, and because of the prevailing practice of estimating fragility levels as essentially constant with frequency without regard for whether any mechanical resonances* are present. Implementation of the specifications is commonly such that design of the shipped item to withstand the shipping shock or vibration is arbitrarily prohibited and for formal purposes survival in shipping is made to depend on the outcome of the container decision process. Yet, for all the furor and frustration that may be associated with this decision process, final container designs typically turn out to have about the same resonance parameters. Finally, in principle at least, the effect of the drop test is to require complete survival of container and contents up to heights that are not extreme values of the anticipated environment but somewhere in the middle, while requiring no evidence of survival for greater heights.

Rather than proceed from the findings and interpretations of Chapter 2 directly to final recommendations, it may be beneficial to list and discuss some options:

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1. Require that design of any new container be initiated with and carried on concurrently with the design of the contents.

2. Require that the caging of any hinged or swiveling assembly for shipment be a consideration in the design of the contents.

3. Require that hard points for support in shipping be a consideration in the design of the contents.

4. Require that support in shipping be such that cantilevering will not contribute significantly to vulnerability, and require that this be a consideration in the design of both the container and the contents.

5. Require that support of a flexible item such as a small missile be such that the shipping environment will not significantly excite the first mechanical resonances, and require that this be a consideration in the design of both the container and the contents.

6. Require that any isolators shipped integrally with the contents be inactivated in one way or another unless evidence can be presented to show that they will not complicate the problem of protection in shipping.

7. Prohibit the literal quotation of the <u>legal</u> requirements of a shock or vibration specification as a <u>technical</u> estimate of the fragility of contents to be shipped.

8. Permit or require that legal requirements now quoted as vibration fragility estimates for contents for design of container support resonances be multiplied by a factor of 2 or 3 to relieve the cushion damping design problem unless the contents designer can provide evidence that in the particular instance this involves excessive risk. Prescribe corresponding g-levels as minimum design requirements for the contents in the low frequency range.

9. Require that the contents designer disclose any informal design objectives derived from vibration or shock conditions, such as equivalent static acceleration, or the empirical formula quoted for some space hardware and discussed in the associated interpretation or comment in Section 2.1 of Chapter 2, and let these be used as points of departure for a low frequency fragility estimate.

10. Let the first resonance frequency of the contents, whose excitation can not be suppressed by method of support in the container, be a controlling factor in determining a maximum frequency for the support resonances.*

11. Prescribe a drop test height, such as three feet, for which complete survival of the container will be required; a drop height, such as three feet, for which complete survival of the contents will be required unless the

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contents designer can show that corrective action for a particular container would involve an excessive penalty in weight or performance of the contents; and one or more drop heights, such as five and ten feet, for which the only requirement will be an upper limit on the number of failures in the contents.

12. Prescribe a minimum first resonance frequency for the contents as shipped, such as 50 Hz unless the contents designer can show that this would involve unacceptable penalties in weight or performance of the contents; a corresponding range for the container support resonance frequency, such as 15 to 25 Hz, that is somewhat higher than the range in which it ordinarily now falls as a result of the decision process, so as to require less sway space for shock protection of the contents; and a range for the Q (approximately the amplification at resonance) such as 5 to 9, that is readily attainable without unnecessary effort at damping. If necessary, prescribe two or more minimum first resonance frequencies and corresponding sets of container parameters, with a preference for the highest first resonance unless the equipment designer can show that this involves an unacceptable penalty.

13. Let the sway space be determined by the drop test and associated requirements in accordance with Option 11, or prescribe sway spaces along with the other support resonance parameters of Option 12.

14. Prescribe complete sets of container support resonance parameters, plus any advisable constraints on transmission at higher frequencies, let these be verified with dynamically suitable dummy contents, and let any requirements placed on the contents in accordance with Option 11 be verified by design review, in full recognition that there will ordinarily be no contents resonances in the region of the support resonance frequencies or below.

15. Provide no vibration protection in the container other than precautions such as Options 2 through 6, but provide for drop protection by a crushable cushion, or for better reusability or second drop protection, a cushion that will gradually restore its shape after compression in a drop.

16. Place upper limits on container weight and bulk in relation to the contents weight and bulk.

17. When container - contents pairs are shipped, require examination of arrival inspection reports for evidence of inadequate design of the contents for the shipment environment or of incompatibility of container and contents properties.

These are some ideas that could be used judiciously in various combinations to obtain better design procedures for shipping shock and vibration than those currently in use. Option 1 is advisable except when the contents are so far ahead of the state-of-the-art that the packaging requirements must be uncertain for some time. Options 2 through 6 represent good specification practice for any container design and are examples of aspects that have been deemphasized by the focus of the present decision process. Option 7 through 9 are attempts to make that decision process easier by more realistic estimation of fragility levels.* Options 10 through 13 bring resonance frequencies** explicitly into the decision process to offset an overemphasis on level, as in the problem of isolation systems. Option 14 explicitly separates container requirements from contents requirements, requires tests to verify the former, but avoids any mandatory extensive test program for the latter. Option 15 calls attention to an alternate approach to cushioning, very much in line with much commercial practice. Option 16 would provide a basis for formal negotiation of tradeoffs when container designs based on other factors result in excessive weight or bulk. Option 17 would require that field experience with container-contents pairs be reported to container and contents designers for corrective action as advisable and feasible and for utilization as further realistic background for future problems.

4.4 Recommendations for Packaging Engineering

The present decision process does little either to adapt shipping containers to their contents or to encourage design of the contents to withstand the shipping environment -- or to verify that the impact of qualification specification requirements based on other considerations is such that the design of the contents is already adequate for shipping. It is distracting from the realities of the situation. In spite of the engineering effort that has been forced into this process, Chapter 2 revealed little firm information about the general adequacy of the contents designs for the shipping shock and vibration environment -- only a general feeling that the safety margins are much greater than they are formally assumed to be. But lack of failures in the two rather spectacular missile transportation accidents reported in Section 2.3 of Chapter 2 supports this. Furthermore, it is supported by the fact that commercial equipment, including instrumentation and television sets, subject to no qualification test at all, survives the shipping environment with minimal protection not subject to the Government decision process involving fragility estimates etc., with better than marginal success. Several of the options would make the decision process easier. However, in the interest of economy of engineering effort, it is advisable to prescribe standard parameters for new container designs except when the contents designer can call out specific design features that require more attention. When such features are called out, it is advisable to encourage and allow some latitude for engineering judgment, with the cooperation of both equipment designer and the container designer, rather than impose a strict formal decision process for all situations. This would reserve the deeper engineering attention for those situations that need it and then apply engineering expertise to the problems. Accordingly, the recommendations for revision of the pertinent specifications are as follows:

1. Enforce Option 1 (concurrency of container design) whenever equipment to be shipped during production is out of the research or advanced development phase and committed to development for a military system.

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2. Apply Options 2 through 6 as mandatory requirements during any such concurrent container-contents design process.

3. For new container designs, prescribe one or more sets of support parameters in accordance with Option 14, and generally in accordance with the philosophy of Option 12.

4. If there should be any question about the adequacy of contents design for shipment in a standard-parameter container, let the first consideration in its resolution be first resonance frequencies and frequencies associated with vulnerable design features, and the second be fragility level estimates, with cautions such as are expressed by Options 7 through 9 -- in other words, reflect resonance effects into fragility estimates. Little relative motion within the contents occurs below the first resonance. In connection with possible accidental dropping in shipment, follow an approach similar to that of Options 11 and 14.

5. Provide for alternate container design according to Option 15, with the approval of the customer. It is possible that any equipment whose first resonance as shipped is above 50 Hz can survive the shipping vibration environment without vibration protection. Specification requirements if any should depend on the properties of available cushion materials.

6. The practice of prescribing a container design by drawings, with provision for minor detail changes as necessary to adapt to new contents, rather than prescribing the method of design, is good and should be more generally permissible. It is obviously wasteful to design new containers when existing containers are very nearly adequate. However, each new guided missile is likely to require a new container design.

7. Enforce Option 17 in the spirit intended.

Again, these criticisms and recommendations are not intended as an adverse reflection on any specification writer. Rather, it is hoped that they will stimulate some consensus at higher management levels so that specification writers as well as equipment and packaging engineers can be free of artificial constraints and better able to use their talents and training. Such a consensus should be formed with the concurrence of representatives of writers and other engineers who may be affected.

Note the technical tradeoff. A lower frequency cushion or suspension resonance in the container tends to provide better protection providing no bottoming occurs. But, with limited sway space in the container for acceptably compact packaging, a higher frequency tends to protect up to higher drops by preventing bottoming. In any event, the first resonance of the contents as supported should be at least 50 percent higher than the frequency or frequencies of suspension resonance. Much more efficient packaging becomes possible if the first resonance frequency of the contents is raised by stiffening to a somewhat higher value than it may on occasion have now.

Should there be concern over risks in standardization of container parameters for contents, in the absence of explicit identification of neccesarily fragile design features, that up to now have required special container design procedures according to specification, it is suggested that a review of representative container suspensions for degree of uniformity of suspension parameters be carried out. Should concern persist, it is recommended that a limited number of controlled exploratory tests be carried out. These should include both rough road tests and drop tests, with the former taking place first to gain more information before repairs become necessary. The objective of the drop tests should not be absolute survival up to 3 feet but maximal survival up to greater heights. There should be several types of contents, with first resonance frequency measured, and in some cases raised by stiffening. There should be at least two sets of container parameters, with one suspension resonance down close to 10 Hz and one up close to 20 Hz or higher. Such exploratory tests, skillfully carried out, would make it clearer what tradeoffs between container parameters and contents rigidity are feasible. Such tradeoffs should be part of the technical management scheme.

It should be noted that the risks of standard packaging without detailed decision making for each item would in any event be less for Government funded than commercial contents. Even in the absence of explicit instructions on first resonances or special environmental test intended to make the designer drive first resonances to higher frequencies unimportant in the shipping environment, ordinary Government environmental qualification specifications for the contents, motivated by anticipated conditions of use of the contents, tend to have such an influence on the designer whether he is aware of it or not. In typical commercial design, the only such influence on the designer comes from qualitative rules of good engineering practice.

Partly to decrease test cost, the dwell test for the entire container plus real or simulated contents, at the isolation resonance frequency, should be eliminated, and other evidence used as necessary to ensure that the cushion material or suspension springs will not fatigue in transit.

4.5 Cases Excluded

No specific changes are suggested for situations where modelling studies are now applied or where safety is critical. The former category includes large missile transporters, packaging for space hardware and packaging for contents with nuclear materials. The latter category includes packaging for nuclear materials and packaging for conventional munitions.

In addition, the application of commercial packaging to Government contents will be left for conclusions to emerge from experience.

4.6 Preparation of Environmental Specifications

Currently, the preparation of specifications is much like the writing of engineering standards for measurements, instrumentation etc. -- by a large committee in order to bring to bear an adequate representation of expertise and ensure representation of all who will be affected. In the case of standards, which are very useful guides for both expert and novice, final consensus is by exhaustion -- the participants often admit that a standard is nearly obsolete by the time it is issued. But standards are primarily matters of technical validity and do not involve the more nebulous considerations of management that are inherent in Government specifications. (Here, the latter category is intended to include documents that may be labelled standards but by reference or quotation commonly become legal requirements on the contractor in Government contracts.) For specifications to avoid the sorts of difficulties reported here, it is essential that some of the more important and more difficult issues be isolated for consideration by a smaller group of experts.

4.7 Customer-Contractor Responsibility

The Government, by its present method of writing shipping container specifications, has inadvertently taken the responsibility for the contractors engineering decisions on protection of contents. The implication is that the stated factors must be considered according to the given procedure, and only these factors need be considered. The specification writers, and later the packaging engineers, get so hung up on the environment-fragility comparison that there is little opportunity to consider other equally important factors. The proposed changes should be implemented in such a way that responsibility for appropriate and adequate engineering is returned to the contractor.

CHAPTER 5

SHOCK AND VIBRATION ENGINEERING, GENERALLY

The survey did indeed disclose some problems. The decision process for packaging, controlled directly by shock and vibration test specifications, was found to be cumbersome, without really optimizing the cushion designs, or even tailoring them to individual applications. Ostensibly scientific, it admitted fragility data having little relation to reality and obscured any sense of the dynamics of the equipment to be shipped. Isolation was found to be frequently a trap for the unwary engineer, promising a simple solution but often actually compounding his problem. The technical risks were usually a result of inadequate collective understanding of the dynamics of the equipment and support structure.

But it would be artificial at this point to continue any separation of isolation and packaging from the rest of equipment shock and vibration engineering -- either technically or as a challenge in technical management. The mechanical resonance (or resonances, in three dimensions) associated with isolation and packaging is merely one of many interacting resonances in the equipment-isolator-support system -- usually the lowest in both frequency and Q, and usually the first in the equipment transmission path, but not otherwise significantly different. Technical management decisions, either locally or by way of environmental specifications, to facilitate crossing organizational lines to ease the isolation and packaging problem would be little short of those required to make shock and vibration engineering generally more effective.

Shock and vibration engineers today are found primarily in structures organizations (in response to structural needs) and in environmental test laboratories (in response to environmental specifications) -- seldom in equipment development organizations and seldom participating in equipment development. Environmental specifications are intended to stimulate attention to the environment during development, but for shock and vibration they do not have this effect. As there is no explicit requirement for such effort in the specifications, contractor management will seldom approve any, and customer representatives will seldom approve funding for it.

The isolation and packaging survey underlying this report is a direct reflection on the state of the entire art of equipment shock and vibration engineering and the technical management of it by specifications. Decision making could not be so inept in the more restricted area without being comparably inept and inefficient in the whole.

Organizational aspects are best left to the discretion of the individual contractor, but the customer has the privilege of requiring through environmental specifications a developmental* program in shock and vibration as well as a test at the end.

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*In the event that any reader lacks experience with the distinctions between the phases of research, development and production, he is referred to Appendix 6.

5.1 Recommended Changes in MIL-STD-810

Recommended changes in MIL-STD-810 and related specifications will now be outlined. Clarification and justification beyond that of the introductory section above will follow immediately.

Merely increasing the detail and extent of formal requirements in a specification runs the risk of creating or expanding a special contractor group for keeping the contractor responsive during proposal effort (no contractor can afford to take a risk on this) without necessarily having any beneficial effect on the product.

It is proposed that the shock and vibration test requirements be retained as is except for changes to incorporate the recommendations of Chapter 4, convert all spectral requirements to minimum spectra without tolerances, and clarify fundamentals. However, qualification test results should be accepted as only partial evidence of design adequacy. In addition, there should be a requirement for an engineering development strategy, to be proposed in the RFP, reviewed, approved and funded, and to be reported on later to the customer in the same way as other engineering development. Further, the appropriateness and effectiveness of the contractor's shock and vibration development program should be considered by customer representatives in ruling on requests for deviations and waivers. The development program may include but not be limited to the items listed below, which are not individually mandatory but offered as examples for consideration by the contractor, according to the nature of the equipment under development:

1. Application of rules of thumb in mechanical design.

2. Physical modelling for measurement of resonance frequencies revealed in transmission or mechanical impedance, design modification to avoid unfavorable frequency relationships, interchange of frequency information with any subassembly subcontractor, and negotiating whether any necessary design change may be made in the subassembly (the subcontractor may include a contingency for this in his cost estimate) or in the prior transmission path.

3. Mathematical modelling for response investigation, starting with the simplest model considered useful at low frequencies and increasing the complexity as necessary as the frequency range is extended upward, so long as this continues to be useful.

4. Early application of qualification test conditions to identify modes of failure.

5. Identification, as data become available, of any dominant frequencies in the actual environment and modification accordingly of the equipment or the prior transmission path as judged prudent, aided by whatever interorganizational negotiations may be necessary.

6. Consideration of the use of sound absorption, when sound rather than mechanical motion is the primary source of excitation, and an absorber can be effective without severe weight penalty.

5.2 Preservation of the Qualification Test

There are two reasons for preserving the shock and vibration tests rather than depending entirely on the developmental programs recommended here. The first is that there is still some virtue in a simulative test whose severity is related as closely as necessary or feasible to the actual environment. The second, less widely recognized but equally important, is that potential failures of functional equipment can not be predicted reliably in advance.

In the middle fifties, Robert Lusser (who inadvertently stimulated but did not himself initiate the statistical reliability testing movement, to be discussed later in this chapter and in Appendix 8) proposed that conventional environmental testing be abandoned, that advance predictions be made of the failure modes of the equipment, that representative items be tested systematically to failure to determine the safety margins for each failure mode, and that redesign be carried out to ensure that each safety margin exceed by a suitable factor the standard deviations of the environment and of the strength in production. As illustrated by Lusser in terms of static stress, this proposal presented a beautiful lucid picture, but it was too radical for adoption by any Government agency. In retrospect, it had several fatal flaws. It depended too much on strengthening the failure points as opposed to controlling the transmission paths. Test to failure, simple enough for static stress, would have been too cumbersome in systematic application with environments specified by spectra and therefore functions of frequency as well as time. Indeed, Lusser, entranced by his simple picture, never came up with a practical test-to-failure procedure. The shock and vibration at the failure points is much more difficult to predict than the excitation input to the equipment. Finally, as noted above, it is not possible to predict failure modes of functional equipment reliably in advance of test.

It should be recognized, however, that the end objective of environmental test is not simulation (which is at most a means to an end) but to help induce design such that the equipment will survive the actual environment and perform as necessary. For example, if the first resonances of an equipment to be shipped are above 50 Hz or so (preferably not grouped together immediately above such a frequency limit) damage during transportation is unlikely. The precise level of test excitation at lower frequencies is unimportant so long as it offers sufficient inducement to raise resonance frequencies out of the frequency range and at the same time does not cause serious difficulties to the development team. At the lowest frequencies, unless an isolator is to be included in the test item, either 1/4 or 1/2-inch amplitude (in terms of swept sine wave excitation) is satisfactory, regardless of the actual conditons. In either case, if there should be a resonance this low in frequency, other than in a cable whose motion is so restricted it can not stress significantly the connections, the response will be at least ten times as great, or 2 1/2 to 5 inches, which, in typical compactly constructed equipment, will produce an intolerable rattle and induce immediate redesign. Once all resonances are moved upward well outside of this range, the relative motion induced by either amplitude will be seldom sufficient to cause collision or significant stress.

But any reader who clings to the idea that the qualification test should remain the sole evidence of design adequacy should reflect on the way that the tests are negotiated and implemented. Qualification test requirements are typically negotiated at the beginning of a program, in the absence of data, with everyone present who has fears about the outcome, with shock and vibration engineers in a small minority, and with most of the participants anxious to get back to questions that are more related to their own specialties and have clearer answers. Then the test conditions become legal requirements in the contract and extremely difficult to change when data if any become available. In the meantime, they serve as a source for subassembly and vendor specifications.

Few considerations have contributed to more errors of engineering judgment or had a more devastating effect on progress in shock and vibration engineering than the fiction, inadvertently created by the way specifications are written and implemented, that survival of a subassembly in shock or vibration test is incontestable proof that the subassembly would also survive in the complete equipment subject to the same test. Newly designed subassemblies have been carried all the way through development to early production only to find that they could not survive shock or vibration when installed into the complete equipment.

But the practical realities are worse than this suggests. Whereas a few contractors multiply up subassembly test severities by a chosen factor for additional assurance, it is more common to leave the derivation of subassembly and vendor item test conditions from complete equipment specifications as a clerical exercise, subject to no screening as to the actual benefit of the tests derived, and subject to no supervision or consultation by persons qualified in shock and vibration engineering. Fragments of the equipment specification are quoted without concern as to whether they add up to something that makes engineering sense. Shock test conditions for vendor items are often specified only in terms of peak acceleration, which conveys no definite engineering meaning, as it can be complied with by use of a centrifuge, without inducing any transient shaking at all. A centrifuge test, so labelled, and arrived at as part of an engineering plan, might be sensible and have welcome benefits, but test conditions should not be left to clerical whim.

Therefore the position taken in this report is that while the qualification test should be preserved, with some refinement but without significant increase in complexity, it should be supplemented by a developmental strategy, to be proposed by the contractor for review, approval and funding, which will apply an appropriate amount of attention to the dynamics of the particular hardware. The existence of such a negotiated strategy for development of an equipment should be an effective guarantee that shock and vibration matters will not be left to clerical decision and an effective assurance against errors of engineering judgment. In all probability, once the engineering and technical management traditions appropriate to this approach have emerged in the course of repeated application and evaluation, it may well recover its own cost, while assuring the customer of a better product with improved reliability and decreased maintenance requirements.

Typical equipment differs greatly in dynamics from typical major structure, except in some instances for immediate supporting structure. At one extreme, it is massive and dynamically simple, as in the case of a motorgenerator set.

At another, which is more characteristic of the majority of cases, it is a succession of smaller and smaller parts attached to larger ones, as for example resistors, capacitors etc. attached to a terminal board, with various vulnerable mountings and connections. The progression from large to small is a natural way to design and is favorable for resistance to static loads, but it can be disastrous for dynamic loads if any resonance frequencies along a transmission path are in near coincidence. This combination of design characteristics can result in violent whipping of smaller parts and is one of the most important reasons for failure or malfunction in shock and vibration tests. Fortunately, it does not require sophisticated computation, meticulous selection of design parameters or severe weight penalties in corrective redesign.

It is a coincidental result of the way specifications are written that shock and vibration on the one hand and noise control on the other, while sharing essentially the same technology, have developed their respective engineering methodologies from exactly opposite viewpoints.* In noise control, the vulnerable element, namely the human ear with its associated nerve system, is considered unalterable except for the possible addition of an ear plug or noise shield. The entire emphasis is on the control of the source mechanisms and the mechanical and acoustical transmission paths. In shock and vibration, the environment is considered unalterable in principle, except by means of isolators, which as noted above are not always successful in practice. Almost the entire emphasis is on ruggedizing the failure points -- there is little or no conscious concern with control of transmission paths in design. But what yields benefits in noise control must have potential benefits for shock and vibration. The present proposal would reduce such benefits to practice.

5.3 Vulnerability and Survivability

The present proposal is in effect to supplement test to specific levels of shock and vibration environment with a simple developmental strategy that can yield benefits regardless of the actual level of environment the equipment must survive. Usually, a test level is intended to represent an upper limit of the actual environment, but it should help our perspective to recognize that there are important environments for which no practical upper limit can be assigned. The logical objective is not guarantee of survival in such environments but maximizing the probability of survival.

In wartime, it would be advantageous if weapons systems, their components, and associated equipment have a reasonable chance of surviving enemy action. Logically, one could take the position that the most extreme environment an equipment should be required to withstand is the environment at which the airframe or ship's hull is destroyed or the people on board are killed or incapacitated. But the closest one would be able to come to this would be a crude estimate. Such fragilities are seldom supported by meaningful data and in any

*C.T. Morrow, "Noise control versus shock and vibration engineering", Journal of the Acoustical Society of America, Vol 55, No. 4, April 1974, pp 695-699.

event are not necessarily directly comparable to equipment shock excitations. Establishing an arbitrary test level, or perhaps a succession of several increasing test levels, for use in the course of development can be an effective tool for gaining survivability. However, success can be obtained more quickly if the supplementary development program recommended in this chapter, which will provide benefits regardless of the eventual level of excitation, is also utilized.

Formal concern about effects of enemy weapons systems on friendly hardware has tended to focus on nuclear blast effects and to follow a separate course with higher security classification than shock and vibration generally. In recent years, there has been a growing concern also about pyrotechnic shock -- a matter whose decision requirements are subject to much controversy and bewilderment. Most shocks in missiles and space vehicles are pyrotechnic in origin, but the term pyrotechnic shock has come to mean excitation by explosives or enemy projectiles in immediate proximity to a point of vulnerability, with enormous peak accelerations and with energy concentrations at high frequencies -- near to or above the nominal upper frequencies of typical shock tests. The most notable examples of a welding of vulnerability and survivability with ordinary shock and vibration engineering are the Navy shock test machines in some of their applications,* the Navy Floating Shock Platform test, commonly referred to as the barge test,** and a test carried out on the amphibious command ship Blue Ridge near San Diego in 1975 just prior to the 46th Shock and Vibration Symposium. In an extension of test realism to almost the ultimate, the Blue Ridge with its shipboard equipment was subjected to a series of underwater explosions, after which damage was analyzed and corrected. Most of the failures were simple and could have been avoided by fortified engineering judgment. At meetings such as the Shock and Vibration Symposium, continuing treatment of aspects of vulnerability and survivability that are not subject to the highest security classifications would provide much to enrich ordinary shock and vibration engineering.

5.4 Minimum Spectra

The application of maximum and minimum tolerances to nominal shock and vibration spectra has seemed like a logical and convenient thing to do in the preparation of specifications, but in practice it confuses responsibilities and adds unnecessary effort and expense. For a test item whose design is not marginal, it can add unnecessary test effort to hold the environment below the upper tolerance. Furthermore, if such an equipment survives a test shock that is subsequently found to have exceeded in some frequency range the upper tolerance, nothing is gained when the customer representative orders a retest. A specification is not satisfactory unless it generally leads, directly or indirectly, to correct decisions even when it is first interpreted by people who have little special technical knowledge.

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*Harris and Crede, SHOCK AND VIBRATION HANDBOOK, Chapter 26, McGraw-Hill, 1976.

**E.W. Clements, SHIPBOARD SHOCK AND NAVY DEVICES FOR ITS SIMULATION, NRL Report 7396, Naval Research Laboratory, Washington, D.C., July 14, 1972.

MIL-STD-810 should state explicitly the relative responsibilities of customer and test organizations in respect to shock and vibration qualification test. It is the customer's responsibility to ensure, insofar as feasible and practical, that the test condition is adequate (e.g. a minimum spectrum), while maintaining sensitivity to the need for minimizing overtest and any consequent cost or schedule delay. It is the test organization's responsibility to carry out the test with as little overtest as practical, and to cooperate with the customer and development organizations in the negotiation of any design changes or requests for deviations or waivers.

5.5 Fundamentals

The fundamentals that need attention are random vibration (to a minor degree), shock spectra and the question of mechanical versus acoustic excitation.

Much of the technical progress in shock and vibration in recent years has stemmed from the introduction in the middle fifties, by way of the Air Force ICBM program, of the random vibration test and the use of shock spectra in specifying shock tests. The former ignited a decade of controversy over fundamentals, violent at times, which nevertheless subsided completely as test equipment became generally available. The latter stimulated little controversy at the time but remains to this day a matter of confusion and bewilderment.

Today, random vibration, compared to shock or periodic vibration, is the simplest excitation to deal with conceptually -- except for some minor confusion over the practical role of the probability density function. What the wide-band probability density function of the excitation may be is almost irrelevant, as anything but the Gaussian distribution is rapidly altered by transmission along the transmission path. True random vibration tends to become more Gaussian, except for effects of any nonlinearities associated with failure mechanisms at failure points. Pseudorandom vibration is sometimes generated as a set of non-Gaussian narrow-band signals which are summed into a broad-band Gaussian signal for the shaker. This results in a useful test, but any assumptions about the distributions at the failure points can be wrong -- transmission tends to let narrow bands dominate and therefore makes the distributions less Gaussian. Nevertheless, distributions seldom receive more engineering or data reduction attention than they deserve and do not constitute a serious technical management problem.

The continuing confusion and bewilderment over the shock spectrum arises from the fact that its initial use in the Navy and its introduction into Air Force programs predate both the availability of the electronic shock spectrum computer as an alternate to the reed gage and the discovery of a simple proportionality (factor $2\pi f$) between the undamped residual shock spectrum and the magnitude of the Fourier transform. Consequently, the traditions of shock testing were established in terms of what is now known as the maximax spectrum -- a concept that should now be obsolete except for special situations. But the reed gage could not separate residual spectra from maximax.

It may be instructive to review the pertinent statements of AIRBORNE ELECTRONIC EQUIPMENT WS-107A, Environmental Test Requirements, dated 3 January 1956, which served as the initial specification for Atlas and Titan. Paragraph 3.2.2.9 begins with the requirement "Shock - A shock whose shock spectrum in both plus and minus directions is at least 100g from 100 cps to 700 cps." Paragraph 6.1.3 includes a clarification, "A preferred pulse shape is a terminal-peak sawtooth which rises to 100g in approximately 6 milliseconds with as sharp a peak as possible and a minimum of superposed oscillation and drops abruptly to zero, as may be obtained by fastening the component to a rigid carriage and dropping it onto a properly shaped lead pellet." This paragraph also defines the shock spectrum as "a plot of the peak response of a simple undamped resonant member in terms of acceleration vs. the frequency to which the resonant member may be tuned.", describes the reed gage, and points to an analog computer as an acceptable alternate for the future.

The basic requirement was not a pulse but a spectrum, properly an undamped spectrum, and quite properly a minimum spectrum. Although the residual spectrum (obtainable by observing "resonant member" response only after shock termination) was not explicitly indicated, the phrase "in both plus and minus directions" eliminated from the ICBM program the traditional Air Force square wave and half-sine wave shock pulses, which have nulls in their residual spectra -- the negative maximax spectra for these pulses are the mirror images (negative, not positive) of their residual spectra. Consequently, the novel terminal-peak sawtooth was offered as an alternative, which had the effect of adding this pulse to the standard Air Force shock pulses.

It should be noted that the Navy, then as now, specified, not environments, but shock test machines with suitable adjustments, sometimes modified for particular applications, but in any case used the shock spectrum as a check on the environment created. The Air Force specified shock environment in terms of standard acceleration pulses, but any equivalence to shocks to be simulated was established, for lack of a better idea, by naive time-domain comparisons -- the Navy procedure had either not been widely and clearly explained or had not made sufficient impression. The result, in Air Force programs, although not widely recognized even now, was often a test shock with excessive energy at low frequencies and deficient energy in the dominant frequency range of the shock to be simulated. The objective of elimination of this time-domain comparison was an important motivation behind the statement of the shock requirement for Atlas and Titan. The spectral magnitude and shape were a pure guess, in the absence of data, at the character of staging shocks. Curiously, this test shock environment was actually imposed only as an inoperative requirement, to simulate shipping and handling, because of an opinion that there would be no shocks in flight. Thus a test requirement subsequently of significant historical importance almost became eliminated from the specification!

In accordance with the responsibilities outlined in the previous section, the customer should not be specifying shock pulses that have residual nulls or specifying maximax spectra that can be complied with by using shock pulses that have residual nulls, in any important frequency range, unless such pulses are to be applied more than once with more than one duration, so as effectively to fill in the nulls. These nulls indicate frequency bands where any shaking induced in equipment under test does not persist appreciably beyond the shock duration -- failure is unlikely except in very brittle material.

If a degree of equivalence is to be established, by means of residual spectra, between a test shock and a shock to be simulated, the latter will seldom have a definite ending and therefore the undamped residual must be used -- the damped residual spectrum will not be defined. In any case residuals are more representative of total shock time history than damped residuals, and more indicative of damage potential, especially in multiple-degree-of-freedom systems, than maximax spectra, which tend to be dominated by the original pulse, which remains essentially unchanged in transmission through a test item except for some superposition of transients.

The undamped residual shock spectrum may be regarded as the Fourier transform converted from units of velocity to units of acceleration. It is easier to recognize danger limits in terms of acceleration or relative displacement than velocity.

In the middle fifties, it was necessary to justify the shock spectrum as being representative of accelerations that may occur within a test item (more nearly true than for excitation time-domain parameters such as peak acceleration or duration), but this has been taken too literally and has led to a proliferation of unstandardized values of Q for maximax spectra, from 10 or so on up. There has been excessive preoccupation with the single-degree-of-freedom system. The basic task of a specification, insofar as possible, is to define a minimum acceptable excitation rather than to describe all possible responses, which, except perhaps for low-frequency relative displacement in isolators, are more properly left for the contractor to infer, with due allowance for multiple- as well as single-degree-of-freedom systems.

To ensure a degree of simultaneity of test item responses, it may be beneficial also to set an upper limit to test shock duration, or on occasion, to ensure similarity of test results in different test locations (e.g. production vs. development test laboratories), a nominal duration with tolerances. An unpublished paper by the author, on digital computation of residual shock spectra, shows that the frequency derivative of the phases of the simple undamped resonator residual response is indicative of the apparent starting time of residual transients. In preference to shock duration, this would have the advantage of being finite and definite even for shocks that have no definite endings.

The shock-pulse drop-test tower has a tradition of many years and is simple and inexpensive. The electronically driven shaker system, used as a shock test device when large energy at low frequencies is unnecessary, has the advantage of versatility. In the course of a test program, it can be used to determine the effect of a concentration of energy near one frequency, or a dip in energy near one frequency to simulate dynamic loading of the actual supporting structure. Instrumented with force gages at the mounting points, it could be used for simulating acoustic shock excitation, specified by a minimum undamped residual shock spectrum of force (treated as a purely mathematical concept) or possibly as a minimum Fourier transform of force.

Finally, it should be recognized that acoustic excitation is not an environment independent of the vibration (or mechanical shock response) associated with it. The criteria for its imposition should be based, not solely on the level of acoustic excitation to be simulated, but on whether the dominant transmission path for the actual excitation is judged to be acoustical or mechanical, whether the actual acoustical excitation may be an effective flanking path past a mechanical isolator, or whether acoustic excitation has practical advantages in system test over simultaneous excitation of various subsystems or equipments by separate shakers. It should not be imposed without restrictions on the mechanical support for the test item. With engineering discretion, there are three logical choices -- a zero-mechanical-impedance support (e.g. bungee cords) to simulate a missile flight condition, a near-infinite-mechanical-impedance support to simulate attachment to a large rigid body, or a section of the actual support. The intent is to ensure that the mechanical resonances of the test item are similar in test to those of actual use. The third option may also supply some realistic mechanical excitation.

5.6 Rules of Thumb

It is essential that the equipment design team be able to arrive at an approximation to final mechanical design without a cumbersome procedure for each detail decision. One common rule of thumb is design to a uniform predetermined maximum acceleration or stress, thereby converting a potentially complicated dynamical problem to a simple static one. But this by itself can involve severe weight penalties as the maximum is increased, without being an efficient method of achieving reliability. Such rules of thumb need to be retained and expanded so as to provide a more effective initial attack on the design problem, in realistic recognition of the possible amplification of shock and vibration environments as they are transmitted through interior structure to potential failure points, without aggravating the current overemphasis on failure point strength as opposed to environmental control along the transmission path, and without overruggedizing portions of the equipment that already have large safety margins.

In Section 2.1 of Chapter 2, a compromise was reported that, with changes of numbers according to the particular situation, might well serve as a model for widespread application. It utilized successively higher static design accelerations for successively smaller subassemblies, thereby allowing for some environmental amplification beyond that of a single-degree-of-freedom system. At the same time, it placed a degree of indirect control over the amplification by prescribing successively higher minimum frequencies for resonances of successively smaller subassemblies. Accordingly, the probability of coincidence of first resonance frequencies along a transmission path became quite small, and the probability of more general coincidences was at least decreased.

5.7 Physical Modelling

In most cases, further precautions will be beneficial. As the mechanical design for an equipment takes form, much can be learned in advance of functional test by constructing one or more models, simulating at least the primary internal structure of the equipment, measuring resonance frequencies, preferably by the Lissajous technique described in Appendix 4, and then simulating or constructing subassemblies and making resonance frequency measurements with them both separate and attached. An alternate method for estimating frequency relationships is to strike the model, pick up the induced transients by accelerometers, a hand-held probe, or even a nearby microphone, and obtain the frequencies of the transients by an instrument such as a fast Fourier transform analyzer. Any increasing minimum frequency prescription for subassemblies implies some such measurements, but once an engineer who is adept at this has started work on an experimental setup, he can rapidly explore frequency relationships and carry out detuning of frequencies along the transmission paths so as to minimize the amplification.

Note that the techniques recommended here are simple and inexpensive to apply, require no elaborate computation or precision redesign, and do not necessarily involve a weight penalty. With attention to impedance concepts, these techniques can make it possible to estimate the performance of an isolator design primarily through frequency relationships if mounting the equipment on a mechanical isolation system is under consideration.

5.8 Mathematical Modelling

At the time of writing, computer simulation for equipment shock and vibration tends to go to either of two extremes, neither of which is satisfactory. Available shock spectrum computers, used as simulators, have no capability beyond the simple resonator, and are of no help in controlling transmission within an equipment. At the other extreme, exacting simulation of dynamics down to the last detail has, except for inevitable inaccuracy, some utility for structures, but is of little help in equipment development. In structures, anticipated design alterations seldom make marked changes in dynamics, but in equipment, such changes should be the objective. Some of the simplest and most effective mechanical design changes in equipment during development, such as addition of a strut to provide additional support for a circuit board, would change the program as well as the parameter data. Therefore a program that is t detailed is not a vivid way of suggesting design changes and is cumbersome ir verifying their effect.

It is therefore proposed that response simulation by computer, using only lumped dynamical constants to avoid complications from resonances above the frequency range under study, proceed initially with the lowest frequency range and the simplest model that are judged useful for investigation. Then the upper frequency bound should be increased and the model expanded as necessary so long as the simulation technique is judged useful as a design aid. The engineer should be spared the problem of establishing a new computer program after a design change or frequency extension. A set of ready made programs, covering most hardware configurations of potential interest, should be available in the computer for immediate use according to the engineer's need or whim. These should provide a simple means for predicting responses to defined excitations after each proposed design change. Unpublished work by the author, demonstrated on an inexpensive personal computer at the 51st Shock and Vibration Symposium, in San Diego, in 1980 has shown one way of accomplishing this for shock, even for nonlinear systems. This could be used for vibration, but would be cumbersome and slow. Faster approaches to vibration of linear systems are feasible.

With sufficient skill in physical modelling, design of equipment can be perfected sufficiently without much computer simulation. However, the latter is at least useful in verifying the effect of accumulated design changes, and is particularly more convincing than a physical modelling report by itself to people who have little technical insight into shock and vibration.

5.9 Informal Qualification Test

Early application of qualification test conditions, when functional or partly functional equipment becomes available for test, permits identification of failure modes that might otherwise be overlooked. The swept sine wave test, while not realistic in a simulation sense, has the often important capability of associating a frequency of resonance with a failure mode -- a frequency that otherwise might be difficult to measure.

5.10 Actual Environment

It is not feasible on a routine basis to require that qualification test conditions reflect in detail the spectral shape of the actual environment, because it can not be done at the beginnings of programs, it would involve contractual negotiations as environmental data if any become available, it would complicate the test, and obtaining comprehensive shock and vibration data is not always feasible or within reasonable cost or schedule allotments. However, evidence of any dominant frequencies or gaps in the actual environment should not be merely ignored. One option for the contractor would be to apply such evidence to more informal exploratory environmental tests, utilizing the versatility of the electronically driven shaker, and utilize the results in support of waivers or deviations in the formal qualification test. One option for the customer, as evidence of spectral peaks is found, would be to require exploratory tests.

If a frequency of dominance coincides with a frequency of special sensitivity of the equipment, it may become necessary to negotiate an equipment design change, versus a structural support design change, versus the addition of a mechanical isolator if there is room. The first option, if feasible, has the virtue of requiring little interorganizational negotiation. The second option is unprecedented in equipment environmental specifications, which tend to give the impression that the environment is invariant and not subject to alteration by any engineering actions. Yet it may sometimes be the best solution, especially if the equipment is a standard item intended for many applications, or functional requirements would make its redesign difficult. The third option would add parts to the inventory and maintenance program and might not solve the problem.

Evidence of dominant frequencies can sometimes be obtained, in advance of quantitative data on the actual environment, by striking the support structure with a mallet or other semi-hard implement and measuring the frequencies with a FFT analyzer, or by using the Lissajous figure techniques of Appendix 4.

5.11 Col. Swett's Presentation on Statistical Reliability Testing

A precedent has been set for the alteration of a specification, namely MIL-STD-781, through the influence of an investigator who had been outside the usual review team for specification alteration or approval. Some of the historical background of this specification is given in Appendix B as an example of the strange recommendations that can be made when negotiators take the idea of incontestable proof of design adequacy too seriously, focus too blindly on one apparent deficiency in specifications, and have no vision of the technical management role that specifications should have. In the opening session of the 45th Shock and Vibration Symposium, at Dayton, Ohio, in October of 1974, Colonel Ben H. Swett, recently of the Pentagon, made a presentation entitled Avionics Reliability,* which was primarily a comparative study of MIL-STD-810, the specification most commonly invoked for avionics qualification testing and MIL-STD-781, the specification covering statistical reliability testing -- the planning and executing of sufficient tests over a sufficient time to obtain a mean time between failures (MTBF) that can be indicative of field experience. He found the two specifications to be mutually inconsistent.

The following are some illuminating and pointed quotations from Col. Swett's presentation:

> "I believe the fundamental problem is institutional rather than technical. The reliability world, as symbolized by 781, and the environmental testing world, as symbolized by 810, have been institutionally isolated within the Command and, as it turns out, within the contractors own organization and elsewhere as well. They are separated by the Mil Specs and Standards, by our own regulations, and by our organizational structure. They are appropriately separated by product type -- you have to take a different approach for different usage environments. But perhaps most significantly, they are separated by the viewpoints, attitudes and terminology of the people who inhabit these two worlds. As my immediate supervisor once mentioned, reliability people tend to be 'ethnically statisticians'."

> "The reliability world is basically well organized. We have reliability-maintainability focal points throughout the Command. We do not have a similar structure for environmental testing."

> "Reliability is, like it or not, a sideline to the main thrust of equipment development, somewhat as the Chaplain is often a sideline to a staff meeting."

> "Reliability is based on statistics; environmental testing is based on spec compliance."

> "Reliability applies unrealistic test conditions; environmental testing applies unrealistic test procedures."

*Col. Ben H. Swett, "Avionics Reliability", Shock and Vibration Bulletin 45, Part 2, June 1975, pp 29-42.

Col. Swett discussed the specification hierarchy and then the two particular specifications at some length. There is little reason to reproduce much of this here, but two paragraphs concerning MIL-STD-781 and several concerning MIL-STD-810 deserve comment. Here are two quoted paragraphs about the former:

> "Figure 10 shows the vibration stress called for by Mil Standard 781. It is the only one called for: 2.2 grms, single axis, sinusoidal vibration, at one non-resonant frequency between 20 and 60 Hz. And you'll recall from a previous slide that this is only applied for the first ten minutes per hour of operating time. The first time I briefed this at the Flight Dynamics Laboratory, five people in the audience suddenly burst into laughter at this point. Apparently they knew what was coming next."

> "What happens when you overlay the measured vibration in that same compartment of the A-7 is shown in Figure 11. Obviously, there are infinitely more frequencies and their harmonics operative in that compartment than the 781 test covers, any one of which could be producing resonant type failures."

Although the illustrations are not reproduced here, the technical problem under discussion should be clear, and the more important points made by Col. Swett should also be clear in the quoted text. Indeed, the prescribed acceleration, applied at a single frequency chosen as prescribed, is not only unrealistic but useless for anything but moving loose solder and parts around a little bit. If it had a chance of producing a mechanical failure, one would be able to shake the equipment apart with his hands.

Now, consider some quotations concerning the other specification:

> "I found it amazing that in almost all instances, the equipment is submitted to the stress while turned off, returned to ambient conditions, and then given a functional check or a visual inspection. This might be appropriate for the stresses it will see in storage, transport, or ground handling, but not for the stresses it sees in its operating environment."

This procedure is clearly inadequate and destroys much of the utility of the test. It cannot detect malfunctions that do not involve mechanical damage, and it cannot detect all mechanical damage reliably.

> "810 applies most stress separately, in sequence, rather than in combinations. This weakens the overall test by allowing some failure mechanisms to escape undetected. However, some of the more recent test methods, such as temperature-altitude-humidity combination called for by Test Method 518, reflect greater awareness of this, and are designed to correct it."

The temperature-altitude-humidity combination is indeed an improvement over sequential environments and not particularly more costly. However, when single-axis vibration or shock is combined with other environments to disclose second order failure mechanisms, its quality tends to deteriorate unacceptably.

It is not possible to apply wide-frequency-range three-axis or even two-axis vibration or shock without losing much of the control over spectral shape. For simplicity of test procedure, minimum confusion among participating engineers and technicians, and economy in discovering the more obvious design deficiencies, vibration and shock should be applied sequentially through most of developmental testing, and through much of qualification testing, rather than applied concurrently along each axis or in combination with other environments. Finally, environments should be combined judiciously to obtain additional information -- this should be stimulated by specifications as a matter requiring specially competent engineering judgment rather than merely made routine procedure.

> "Let me hit the second bullet from the top. It's about time we started going to automatic recording of equipment performance during test, and get out of the subjective bit of 'relevant failures', 'non-relevant failures', 'independent failures', 'dependent failures', and all that. 'Failure' should mean to perform within stated limits'."

A caution is in order here. The last sentence, taken literally, as it undoubtedly would be in customer-contractor negotiations, is unsatisfactory. A gyroscope drift slightly out of tolerance, or a radar directionality slightly too large, seldom aborts a mission in the same way as a complete failure of any function, and properly influences system effectiveness through a different type of statistical theory, as explained in Appendix 7, which should lead to its being treated separately from ordinary numerical reliability objectives. Furthermore, accelerated test (at trial stress levels) can be a useful technique in improving reliability relative to catastrophic failures, but is not comparably useful in connection with performance degradation unless suitable scaling laws can be established and used.

> "And the more realistic, combined performance/reliability/environmental test should become the backbone of equipment development and contract compliance, both by levels of assembly and by phases of the acquisition process."

Note the phrase "by levels of assembly" and the word "development". As one proceeds from complete equipment to lower and lower levels of assembly, reliability objectives* become closer and closer to 100 percent or infinite MTBF, implying a need for extreme realism of environmental test and even more prolonged test time for statistical reliability verification. Yet the actual shock and vibration spectra become more and more jagged through the action of mechanical resonances along the transmission paths, so that envelopes or other unrealistically smooth test spectra become inadequate for reliability measurements and ineffective by themselves for reliability development. Col. Swett's efforts led to a useful revision of MIL-STD-781 on Avionics Reliability and the issuing of a policy statement in the form of DOD Directive 5000.40 entitled "Reliability and Maintainability".

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*Appendix 8

5.12 Conclusion

For simplicity in the coordination of the various interacting details, the changes recommended in this report should be prepared, at least initially, for a single specification such as MIL-STD-810. To avoid any necessity for achieving immediate consensus after each detail, it will be advantageous if this preparation is carried out by a consultant in much the same manner as the present report. Large committees tend to reach consensus on each detail in isolation from the remainder of a text, with existing tradition as the dominant influence. However, the changes should be tested for technical management effectiveness, preferably initially with a sympathetic customer and contractor, before official incorporation into the specification, and evaluation of this type of effectiveness should continue after approval. Participation of the consultant in the approval team should be only as a provider of information and as an advisor. The changes primarily for isolation and packaging, based directly on the one-year survey, were recommended in Chapter 4. The more general recommendations for change were summarized at the beginning of the present chapter and discussed throughout most of the remainder.

Briefy, the intent is to retain the qualification test with some modification, but supplement it by a shock and vibration engineering development strategy appropriate to the equipment under development, to be proposed by the contractor and reviewed, approved and funded by the customer. Specifications such as MIL-STD-810 are intended to stimulate development effort in respect to the environments, but this does not happen for shock and vibration. Indeed, the specifications often act as an inadvertent obstruction to suitable engineering effort, by being an inadequate foundation for communication between organizations, and by inadvertently limiting the factors the organizations are permitted to consider. Therefore the qualification specifications should be extended to become development as well as qualification test specifications. Organizational aspects for shock and vibration development are best left to the contractor, but the customer is privileged to request, by way of specifications, that the contractor outline a development strategy for approval, and the customer is obligated to fund it if he expects it to be carried out.

The proposed change of emphasis in MIL-STD-810 cannot achieve widespread success overnight. It is dependent on creation of a degree of teamwork between mechanical designer, shock and vibration engineer, technical manager, and customer representative, and the development of a tradition through experience so that the extent of the appropriate engineering effort can be judged with some degree of reliability. This should be accepted as an objective rather than a limitation. Selection of initial contractors for testing the proposed changes should be governed in part by the need to establish useful precedents as a foundation for future tradition. There are no purely technical solutions to technical management problems. Equipment shock and vibration engineering was created entirely by Government specifications, and the emphasis has not changed since World War II, when it became evident that environmental tests before the end of development were essential.

APPENDIX 1

ORGANIZATIONS AND PEOPLE VISITED

The Author regrets that one meeting scheduled did not take place, because of the untimely death of Dr. Alan Silver, of Litton Systems, Woodland Hills, California, shortly after the appointment was made.

Aerospace Corporation
El Segundo, California

F. E. Cook
D. L. Van Ert
M. Goldberg
S. Rubin
K. W. Shogren

Agbabian Associates
El Segundo, California

F. B. Safford
D. S. Yates

Air Force Flight Dynamics Laboratory
Wright-Patterson Air Force Base, Ohio

A. Burkhard
D. Earls
K. Prather
R. W. Sevy
W. J. Stromberg
M. Venetos
R. F. Wilkus

Army Missile Command, Redstone Arsenal
Huntsville, Alabama

D. M. McDaniel

Endevco Corporation, Pasadena
(now San Juan Capistrano), California

R. Bouche
A. Diercks

General Dynamics Aerospace
San Diego, California

G. L. Getline
P. P. Howie
H. A. Mitchell

Hughes Aircraft Company
Culver City, California

A. J. Curtis
G. E. Mathison
R. D. Stubbs

Hughes Aircraft Company
Fullerton, California

R. Cagle
W. G. Johnson
D. Margolias
N. D. Nelson
R. Vorwith

Hughes Manufacturing
El Segundo, California

R. J. Baylis
L. G. Buhr
H. L. Chandler
K. S. Hochhalter
D. A. Miller
M. J. Peterman

Jet Propulsion Laboratory
Pasadena, California

R. M. Banford
R. T. Dillon
M. Gayman
W. H. Gayman
M. Trummel

Lockheed California Company
Burbank, California

M. D. Lamoree
G. W. Painter
M. A. Rejkowski

Lockheed
Sunnyvale, California

L. Gittleson
T. G. Harrington
W. Hendricks
R. J. Hertzberg
B. R. Horner
A. Ikola
G. G. Jacquemin
D. V. Retzloff

LTV Aerospace Corporation
Grand Prairie, Texas

W. Brock
R. N. Hancock
J. Hutchinson
W. Mussen
B. Spice

McDonnell Douglas
Huntington Beach, California

D. A. Carne
J. W. Lew
D. J. Maxwell
R. W. Mustain
P. F. Spas

Mechanical Research, Inc.
Los Angeles, California

R. D. Galletly
D. L. Platus

NASA Marshall Space Flight Center
Huntsville, Alabama

J. F. MacPherson
R. W. Schock
W. T. Spivey

Naval Ammunition Depot Earle
Colts Neck, New Jersey

D. D. Blanchard
M. S. Gray
H. C. Pusey (SVIC)
E. Rinaldi
R. E. Seely

Naval Missile Center
China Lake, California

G. Adams
W. W. Boyle
T. Inouye
W. N. Jones

Naval Missile Center
Point Mugu, California

D. Everett
C. G. Gerblock
G. T. Pursel
F. Standardi

Naval Ordance Systems Command
Washington, D.C.

G. Mustin

Northrop Electronics
Hawthorne, California

L. R. Beuder
J. Brust
W. P. Dunn
P. M. Fox
C. L. Jones

Picatinny Arsenal
Dover, New Jersey

P. Agresti
R. G. Leonardi
E. Petrocco
S. Ruffini
R. Syvertsen

Rockwell Autonetics
Anaheim, California

T. Hirata
B. Ishino
R. Johnson
H. Kamei
L. Shackelford

Rockwell Space Division
Downey, California

M. T. Hatae
H. Himelblau
V. J. Pachiano
H. K. Pratt

Sandia Laboratories
Albuquerque, New Mexico

J. T. Foley
R. T. Othmer

T. G. Priddy
L. T. Wilson

Shock and Vibration Information Center
Washington, D.C.

R. Belshiem
E. H. Schell
R. H. Volin
(see also NAD Earle)

Spectral Dynamics Corporation
San Diego, California

E. Andress
L. Corcoran
T. Keller

TRW Systems
Redondo Beach, California

M. Barton
J. Conway
H. Kounan
P. O'Neill

Tustin Institute of Technology
Santa Barbara, California

W. Tustin

Wyle Laboratories
Huntsville, Alabama

G. Kao

APPENDIX 2

TENTATIVE QUESTIONS
(Used only as a guide during initial meetings)

1. In what isolator/package-cushion problems have you been involved?

2. What responsibility did you have?

3. What company/customer organizations were involved in the decisions?

4. Were the designs successful?

5. Were you satisfied with the rationale or methodology used--was it cost effective?

6. What environmental data and/or specifications were used as a starting point?

7. What difficulties were encountered in using the data and/or specifications?

8. Were fragility estimates also used as a basis for decisions?

9. What difficulties were encountered in obtaining and/or using fragility estimates?

10. What were the measures of fragility in the frequency range in which the isolator resonances were likely to occur?

11. According to your experience, how have decisions to isolate or not to isolate been made?

12. When decisions have been made to isolate, what have been the ranges of rattle space, resonance frequency and Q in the final designs?

13. How were the rattle spaces, resonance frequencies and Q's decided?

14. How did the reliability of environmental levels/test requirements fragility levels or other data compare with the ranges of rattle space, frequency and Q of Question 12?

15. Were frequencies of periodic excitation to which the isolated item might be exposed ever used in making decisions?

16. Were resonance frequencies or mode shapes of the isolated item or of the structure where it was to be mounted ever used as a partial basis for a decision?

17. Were mechanical impedance data ever used as a partial basis for a decision? If so, how?

18. What were the measures of fragility at frequencies higher than the range in which the isolator resonance would be likely to occur?

19. What sort of isolation requirement was decided on for these higher frequencies?

20. To what extent have shock or vibration test requirements been expressed in terms of force rather than motion? How has this affected isolator design decisions?

21. Have you ever encountered a difference in specification requirements according to whether an isolator is to be used?

22. Have you ever been permitted to modify an isolated item or mounting structure in order to make an isolator more effective?

23. Has the decision to isolate ever been made before the design of the isolated item and/or mounting structure? Why? How did this affect design of item, isolator or structure?

24. Have there ever been conditions, not adequately accounted for in specifications or other initial information, that resulted in bottoming?

25. Have the initial information or methodology ever resulted, in your opinion, in excessive rattle space?

26. To what extent have you used commercially available isolators as opposed to those designed specifically for the application?

27. In connection with packaging, has it been the policy of your organization or customer to design equipment for the shipping environment or only for the use environment, requiring the packaging engineer to be responsible for damage in shipment?

28. Has the primary function of a cushion been to provide high-frequency isolation or to distribute the dynamic loads?

29. To what extent have you used resonant cushions as opposed to those that attenuate force by crushing on impact? Did this depend on the customer?

30. For resonant cushions, what would be your answers to Questions 6 through 28 as appropriate?

31. How would you change initial information and/or methodology to make engineering decisions more cost effective?

32. What other engineers would you suggest that I talk to and with what objectives?

33. What specifications pertinent to isolators would you suggest I obtain?

34. What literature on isolator or cushion design or selection have you found to be most significant in relation to engineering practice?

35. What other aspects of shock and vibration engineering methodology would you suggest for investigation at a later date?

APPENDIX 3

FRAGILITY

Fragility implies a static acceleration or spectral level of shock or vibration that can only marginally be endured without malfunction or damage. On first look, it appears like a useful concept that should serve well as a foundation for a purely scientific approach to isolation and packaging. It is a relatively clearcut concept for static stress and relatively clearcut for failure points (for which it might well be called failure-point fragility) when the responses at these points to shock and vibration are known. Failure-point fragility is the type that is important in the design of airframes and similar structures. The practice of specifying primary environmental tests for equipment in terms of shock and vibration conditions at the mounting points has resulted in a tradition of trying to refer equipment fragility instead to these points. But any attempt to relate the two types of fragility quantitatively would require that the failure points be identified systematically and that the interior transmission be known in detail. Special measurements entirely in terms of mounting-point conditions have been proposed, but fundamental limitations in the concept of equipment fragility would make suspect any general use of such measurements in precise scientific procedures and shed doubt on the cost/effectiveness of the measurements. In practice, engineers have been required to estimate equipment fragility from tests performed on the equipment for other purposes or from specifications for such tests, but, because of designer fears and management conservatism have seldom been permitted to use any engineering insight -- for the most part they have been required to accept each number at its face value without any interpretation.

First, consider the fundamental limitations. A simple mechanical resonator with one mass m, one stiffness k and one linear damper c is sketched symbolically in Figure 1. For excitation by a sinusoidal acceleration at frequency f, the ratio of response to excitation amplitudes is given by

$$A/A_0 = (1 + jf/f_0Q)/(1-f^2/f_0{}^2 + jf/f_0Q), \tag{1}$$

which is a complex number that, converted to polar coordinates, expresses both the magnitude of the amplification and the phase shift associated with transmission. The frequency of resonance is given by

$$f_0 = \frac{1}{2\pi} \sqrt{k/m}\ , \tag{2}$$

and

$$Q = 2\pi f_0\ m/c = \frac{1}{c} \sqrt{mk} \tag{3}$$

is approximately equal to the amplification at resonance. The magnitude of the amplification, plotted in Figure 2 for various values of Q is seen to be significant near resonance for typical resonators. If by any chance a second resonator with negligible mass were attached to a first mass, the combined amplification would be the product of the two appropriate curves and could be devastating at resonance if the two resonators happened to have closely equal resonance frequencies. The amplification curves, derived for steady-state periodic vibration, are applicable indirectly to random vibration and shock and indicate similar trends.

The effectiveness of a shock or vibration isolator is dependent on a tradeoff between the undesirable high amplification at resonance and the hoped for low amplification (below unity) at frequencies well above resonance, but the latter does not always materialize when the realities of equipment and support structure dynamics are considered.

But the primary objective of this appendix is to clarify the limitations of the fragility concept -- first the fundamental and then the practical. Consider a failure point transmission path that involves two successive resonators tuned to different frequencies and is excited at the base by simultaneous vibration at these frequencies. Now, what is the amplitude of the lower-frequency excitation that will barely cause failure? Clearly, this depends on the amplitude of the excitation at the higher frequency. This simple example shows that fundamentally there can be no uniquely defined broadband equipment fragility spectrum.

In shipping container design, most of the time consuming negotiation is concerned with the precise frequency, damping and sway space required in the cushion. For practical purposes, in this restricted problem, the fundamental limitations can be overcome, but not the practical, by assuming that the higher frequency excitation contributes nothing to the probability of bottoming of the cushion, and, once the cushion is installed, nothing to probability of failure of the item to be shipped. Suppose that this item has survived a slow single-frequency sweep vibration test of 1/4 inch amplitude at low frequencies and 2g at higher, and that this spectrum is to be used as the fragility curve of the equipment and is to be compared with the shipping environment. Now, there arise two practical problems. First, the actual shipping excitation is not a single-frequency sweep but may be a random vibration or shock -- comparison of unlike excitations is a common part of the game. Since this is a rather subtle point, the engineer is usually allowed to flounder past it with little restraint on his engineering judgment. Second, the fragility curve selected is only a lower limit -- the mechanical designer has not had the time or funding or incentive to design the equipment to fail at immediately higher excitations. Therefore, literal use of this curve may require unrealistically extreme protection in shipping. For example, the 1/4 inch low-frequency fragility would be an impossible constraint on the motion of the cushion. The mechanical designer will usually compromise to the extent of permitting the 2g high-frequency fragility to be used at low frequencies as well. This makes the cushion problem marginally soluble -- just marginal enough to enlarge the container and create a fatiguing and frustrating negotiation without causing the participants to abandon the approach altogether. But the Q values for the equipment resonances are in all probability at least 10, in typical construction. Therefore, according to Figure 2, the failure points for the first resonances can stand at least 20g rather than 2g, and this higher value may not be an unreasonable figure for all failure point fragilities. At low frequencies where the cushion resonances are likely to be located, there should be no equipment resonances and no significant amplification within the equipment. One may be justified in quibbling over the trustworthiness of the 20g figure, but the point is that negotiation may go on almost interminably about factors of 2 or 3 when the specified shipping vibration inputs may not be realistic to such a factor and there is an uncertainty of the order of 10 concerning the low-frequency fragility. Eventually through exhaustion or some particulary convincing argument by one of the participants there may be a compromise on a cushion and shipping container design that is not excessively bulky or heavy -- in all probability with about the same cushion parameters as in the bulk of other similar situations. Then, as reported in Section 2.3 of Chapter 2, a truckload of missiles in their containers may fall over on its side, bottoming all the cushions hard without damaging any of the missiles.

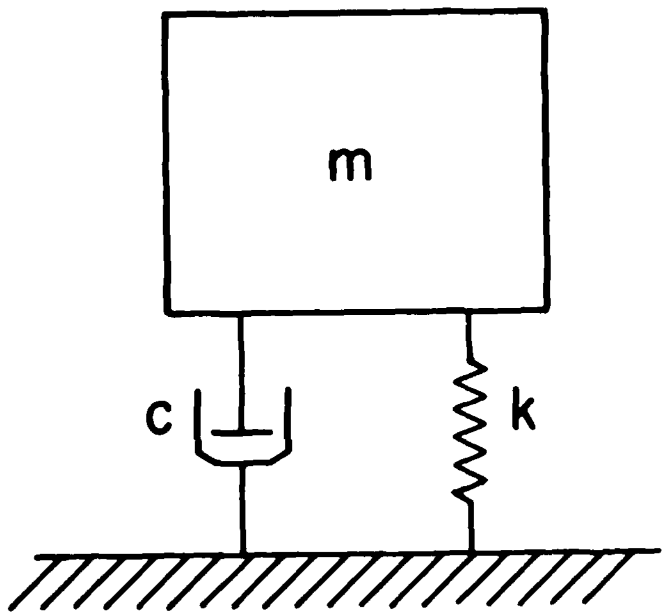

Figure 1. Simple Mechanical Resonator

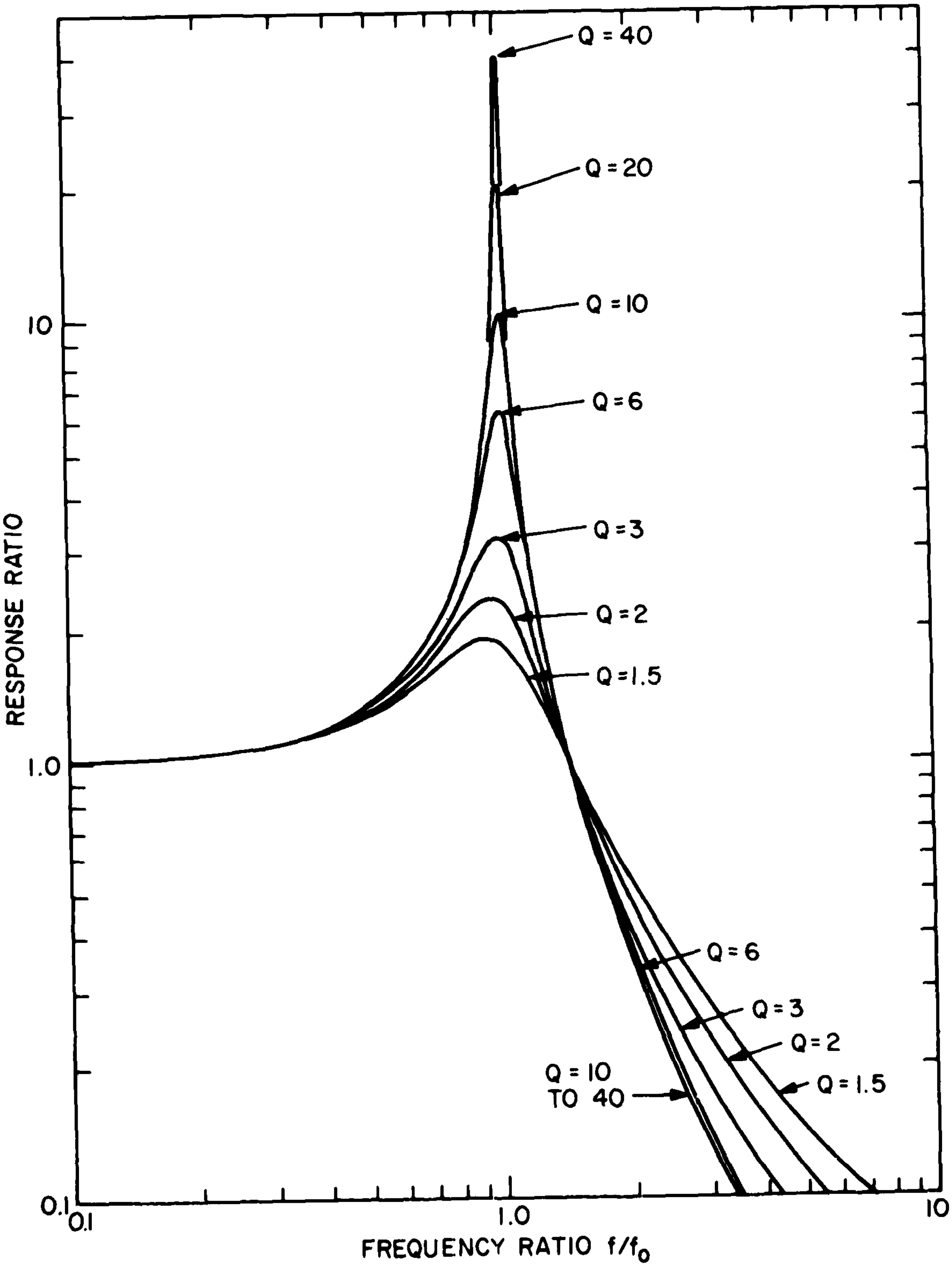

Figure 2. Response of a Simple Mechanical Resonator to Sinusoidal Motion of the Base

APPENDIX 4

MECHANICAL IMPEDANCE, MOBILITY AND RESONANCE

In shock and vibration engineering, there are two ratios that are useful in expressing a relationship of excitation to response versus frequency in a linear or approximately linear system. The first and most common is a ratio of response to excitation in the same units, usually acceleration or displacement. This is used only when the excitation and response points are separate (as otherwise it would be equal to unity) and is called a transmissibility. The second is a ratio of force to velocity. When the exciting force and the response velocity are at the same point in the system, the ratio is called a mechanical impedance, and its inverse is called a mobility. When the points are separate, the ratio is called a transfer impedance, and its inverse a transfer mobility. All ratios are complex, and in polar coordinate form express both magnitude and phase shift. The impedance functions originated in electronics and found their way into mechanical engineering by way of acoustics, which has frequently served as a bridge field. Shock and vibration engineers would be somewhat more satisfied with ratios of force to acceleration or force to displacement, which would relate more directly to indicators of mechanical damage. However, it is simpler to make use of the many useful theorems of electronic circuit theory if the original convention is preserved. While the definitions above are implicitly in terms of steady-state periodic vibration, they are indirectly as useful for random vibration or shock. For simplicity, the discussion to follow will remain entirely in terms of steady state.

The resonances of a mechanical system are indentified by maxima and minima of the above functions and, more sensitively, by associated rapid shift of the phase angles with frequency. In addition, if two systems are to be joined together at a point, the loading of one system by the other can in theory be predicted quite simply from mechanical impedance measured on both systems at the interface points prior to joining, with no need to know in detail the interior dynamics of the two systems. If there are to be two or more junction points, the loading can be predicted from mechanical impedance and transfer impedance measurements.

The single-point loading computation will be explained first. Then the resonance phenomena of a simple resonator will be explored in both its transmissibility and impedance aspects.

The mechanical impedance at a point in a linear mechanical system is

$$Z = F/V = R + jX. \tag{4}$$

This varies with frequency but is constant with time. It is a complex ratio inasmuch as the velocity is seldom exactly in phase with the force. In a passive system, the mechanical resistance R is always positive and dissipative. The imaginary part of mechanical reactance jX typically sweeps through both positive and negative values as frequency is changed. A positive value suggests that energy is being stored primarily in masses during one part of the cycle and released during another part. A negative value suggests that energy storage and release is taking place primarily in springs.

From Norton's (a variation of Thevenin's) theorem in electronic circuit theory, it can be shown that if a device of mechanical impedance Z_1 is attached to a structure of impedance Z_S and vibrational velocity V_S prior to attachment, the velocity at the interface after attachment is given by

$$V/V_S = Z_S/(Z_S+Z_L) \tag{5}$$

The ratio is the same for acceleration and for displacements. Note that V approaches V_S as Z_L becomes small and approaches zero as Z_L becomes large. However, as all quantities can be complex, it is quite possible for the ratio to be greater than unity at some frequencies.

The practical problem with using Equation (5) in the most obvious way, quantitatively, is one of measurement accuracy. This is no problem in electrical systems, but in mechanical systems, different laboratories have been able to duplicate each other's mechanical impedance measurements, which require two instruments at the same point, only within a factor of about 10. With sufficiently widespread use, this would improve, but for the present it remains a formidable obstacle. The solution to achieving some immediate utility is to concentrate, not on magnitudes (levels), but on resonance frequencies. Precision frequency measurements are not required in the typical shock and vibration detuning problem, but would be easier than precision level measurements.

Resonance phenomena were illustrated in terms of transmissibility of a simple resonator in the previous appendix, as a complicator of the fragility concept. Plot of the magnitude of the transmissibility for various values of Q were plotted in Figure 2. It remains to illustrate the rapid phase shift associated with resonance, especially for high values of Q. Let Equation (1) be reexpressed as

$$A/A_0 = \left|A/A_0\right| e^{j\Theta}. \tag{6}$$

Contours of Equation (4) for various values of Q and f, in terms of magnitude $|A/A_0|$ versus phase angle Θ, are plotted in Figure 3. It will be shown later that the phase shift can be very useful help in detecting a resonance.

Resonance phenomena are also evident in mechanical impedance and transfer impedance behavior. For example, the impedance at the base of the resonator of Figure 1 is readily determined from Equation (1). By Newton's second law, the force at the base of the resonator of Figure 1 is given by

$$F_0 = mA = j2\pi fmV. \tag{7}$$

Substitution of this in Equation (1) yields the mechanical impedance

$$Z_0 = F_0/V_0 = j2\pi\, fm(1+jf/f_0Q)/(1-f^2/f_0{}^2+jf/f_0Q), \tag{8}$$

which, like the transmissibility, has a maximum near the frequency, but with approximately zero phase angle. (Note that at low frequencies, the impedance is simply j2 fm --that of the mass moving with the base, obtainable as a ratio from Equation (7).) It follows that while the resonator amplifies motion at resonance, base motion is more difficult to produce at resonance that at other frequencies -- at this frequency, the resonator may decrease the motion of whatever it is attached to. For this reason, it is sometimes used as a "resonant absorber", as, for example, to reduce the motion induced by a rotating propellor at cruise speed. In contrast, the mechanical impedance at the mass, which is readily derived from the differential equation, has a minimum at the resonance frequency, indicating that it takes very little force at that point to produce motion.

If a second resonator is attached to the mass of the first, the response equation may be obtained by multiplying together two expressions of the form of Equation (1), and multiplying again by a loading factor derived from Equations (5) and (8). However, if the second mass is negligible with respect to the first, the loading factor is equal to unity.

As an extreme case, if N resonators are coupled together (i.e. all loading factors are unity) in sequence, and the successive mass ratios are so low that loading is negligible, then the overall transmissibility is the product of the N simple resonator transmissibility expressions. For simplicity, if all the Q values are equal, the overall amplification at resonance is approximately

$$\left| A_N/A_0 \right| = Q^N \tag{9}$$

which illustrates again, with a little pessimism, the tremendous amplifications that can occur within an equipment when resonance frequencies along a transmission path are closely equal.

The simple resonator serves as a first approximation model for a vibration or shock isolator and illustrates the tradeoff between increased motion at resonance and isolation at higher frequencies. But if the equipment to be isolated has a deep impedance minimum in the upper frequency range, it may well be a frequency of particular sensitivity to damage. For example, if the first dynamical approximation to the equipment is not properly a pure mass but two approximately equal masses separated by a spring so that they can vibrate relative to each other in the isolation direction under consideration, they will resonate with the spring and produce at each mass an impedance minimum similar to that of the simple resonator excited by a force on the mass. A simple isolator attached to either mass may not be effective. If the frequency of resonance can not be moved to a higher frequency where it may have less effect, the isolator can be made more effective by attaching it to a nodal point on the spring, or a separate isolator can be provided for each mass.

By similar reasoning, if the structure to which an equipment is mounted has an impedance minimum in a critical frequency range, an isolator may provide no benefit unless it is relocated to a point of stiffer support or a stiffening strut is added to the structure.

In control system theory it is known that a linear system can be completely characterized by its poles and zeros, which are essentially the frequencies of maxima and minima in its transmission versus frequency. Therefore, in shock and vibration as in control system theory, much can be gained by measuring (even crudely) and manipulating the frequencies of resonance.

Impedance resonances in general are not identical in frequency to resonances revealed in transmissibility functions and have a somewhat different significance. Impedance resonances are those that relate most directly to excitation by a force that is conveyed by no structure (or at most a weak structure relative to the equipment), as for example an aerodynamic force or turbulence or sound pressure on a missile in flight -- in other words, these resonances are those of the item excited by a zero impedance source. Transmissibility resonances are characteristic of the item excited by an infinite impedance source and relate most directly to support by a large rigid mass. As a crude example, consider a missile carried under the wing of an airplane.

Most certainly, the way to identify resonance frequencies is not merely to attach an equipment to a shaker, mount a collection of accelerometers connected to a multi-channel recorder, and look for maxima in the recordings as the frequency is swept through the range of interest. The recorders would not be able to distinguish harmonic responses from fundamental. Furthermore, the maxima would be characteristic of equipment plus shaker and might be quite misleading. All resonances must be determined by comparision of response to excitation, measured by an accelerometer or force gage -- an uncalibrated strain gage suitably attached at the excitation point will usually provide an adequate indication of the excitation. For the approximate frequency measurements that are usually adequate, accelerometers will work as well as velocity gages in observing response. A hand-held vibration probe made by attaching a wire or slender rod to an accelerometer or the diaphragm of an earphone will have the advantage of permitting the operator to make response observations at whatever point suits his whim. The instruments do not have to have a flat response -- a freedom from internal resonances that could be confused with those to be identified is all that is necessary.

The simplest and best method of identifying resonance frequencies is a Lissajous technique that involves both magnitude and phase angle. If a reference signal from the excitation gage is connected, say, to the horizontal channel of an oscilloscope, and the response signal of interest to the vertical channel, a Lissajous figure appears on the screen. If both excitation and response are at the same pure fundamental frequency, the figure can be only a straight line, ellipse or circle -- a response at a higher harmonic frequency is easily detected and discarded. A resonance of the shaker merely causes a swelling and shrinking of the figure without change of shape as the oscillator frequency is swept past the resonance. A genuine resonance of the system under study causes a tumbling of the figure in accordance with relative phase changes as well as relative amplitude changes, permitting the identification of even a resonance that is only indirectly coupled to the transmission path under most direct study. Unfortunately, many of the versatile and complicated oscilloscopes in use today do not permit access to both channels or not with a convenient amount of electronic amplification. It is worth keeping an inexpensive simple oscilloscope on hand for this application. Resonances can be identified by comparing the two traces on a fancier oscilloscope, but this is not as sensitive or vivid, and there is more danger of confusion.

The procedure recommended above is quite simple, but it can inadvertently be made complicated and ineffective. Aerospace companies necessarily use large teams for most of their work and are capable of doing the same out of habit for simple laboratory experiments. The author has seen the procedure attempted with the apparatus spread out in the room, one man controlling the oscillator, a second man controlling and observing the oscilloscope, a third man holding the vibration probe, and a fourth man coordinating. When the apparatus was brought close together and operated entirely by one man, progress began.

Furthermore, many engineers and technicians will have an irresistible urge to gravitate away from the simple setup and method outlined above, which may seem crude and inelegant and is not a traditional part of their experience, in favor of more complicated instrumentation. But little can go wrong with the simple approach, and if anything does go wrong, it is readily diagnosed.

There may also be prejudice against an intuitive shifting of frequencies as opposed to a development method that would directly involve more extensive or sophisticated theory. After all, graduate students spend years learning ever more complicated theory, and, on first entering industry, are likely to look down on a simple procedure. But any competent mechanical designer makes the bulk of his decisions in part by intuition. It will be cost effective to have that intuition well guided.

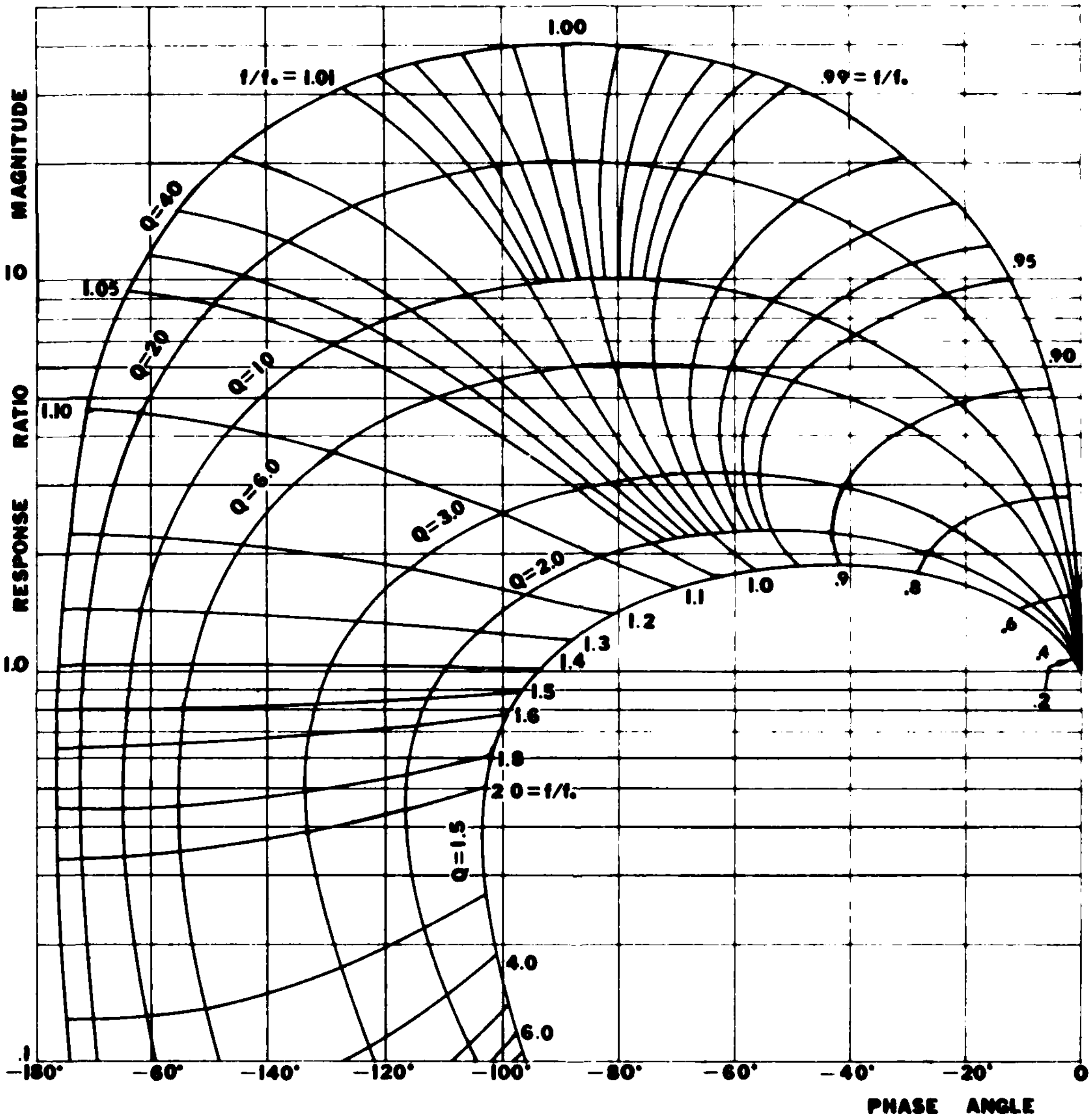

Figure 3. Response Ratio versus Phase Angle with Contours for Q and f/f_0

APPENDIX 5

THE G-5 REPORT

In 1962, the G-5 Committee on Shock and Vibration, of the Society of Automotive Engineers, issued a report entitled, "Design of Vibration Isolation Systems". In the Introduction it states, "It is without doubt a considerable chore to work through the G-5 Procedure given here. However, this is what it takes to choose isolators properly." The report was the result of several years of work and represents the most ambitious attempt ever to put isolator design and selection on a sound scientific basis. Reading the report and the list of participants, both in person and by mail, conveys the impression that it was enthusiastically supported by the bulk of knowledgeable shock and vibration engineers. Yet, the survey on which the present report is based failed to disclose an example of its use.

Actually, even the participants did not have a free choice as to whether to use the report. In consideration of the interorganizational character of the shock and vibration problem, use would in most cases have required management approval, and quite possibly customer approval and funding. But there were other inherent problems. Unfortunately, at the beginning of the committee's deliberations, no one, including the present author, was able to think of an alternate approach clearly enough defined for committee action.

The participants in the G-5 Committee labored heroically to make their report hang together logically and be practical for routine application. They succeeded better at the first objective. In retrospect, the report had the following limitations:

1. It required quantitative measurement of the mechanical impedances of both the equipment and the supporting structure. In almost all cases, this would involve more than one organization, which would lead to a need for management approval, and also complicate the problem of getting comparable data. Several round-robin experiments carried out on prepared mechanical specimens since the date of the G-5 Report have shown large variations, up to a factor of 10 or more, in mechanical impedance measurements made at different laboratories.

2. It required measurement or estimation of equipment fragility as in conventional specification-controlled cushion design for shipping containers. This has frequently been off by a factor of 10.

3. It could not normally be used at the beginning of a development program, when space for the isolator could most easily be allotted. The impedance and fragility measurement requirements implied that the equipment and supporting structure would already be in existence.

4. It required an elaborate matrix computation. This would be the least of the problems in the event of such demand that computers and programs would readily be available for it.

The G-5 Committee had undertaken an impossible task at the beginning, especially with the objective of routine application. It had no travel funding for any survey of existing practices (which did not actually occur to anyone), and little time for the cumbersome process of establishing a consensus on interpretation of any such survey. A questionnaire by mail would have been an inadequate foundation for constructive thinking. The timing of the task was awkward -- the controversy over random vibration concepts was at its peak and was an obstacle to seeing shock and vibration engineering in perspective.

Engineering situations in shock and vibration do arise that would benefit from sophisticated theory and measurement. If the simpler approaches recommended in the present report become adopted for more routine situations, it will be easier to assess the benefit of further sophistication and to acquire data for it when justified.

In retrospect, the G-5 Procedure was an extension into the isolation domain of the required but inefficient procedure used for shipping container design. It retained all the shortcomings of the latter, increased the data taking and computation workload, and introduced additional potentially large errors through the method of use of mechanical impedance. The worst aspect was the implication, quoted in the first paragraph of this appendix, that the procedure should be mandatory, as in the shipping container specifications. Regardless of the merits of an engineering decision procedure, mandatory application is seldom justifiable.

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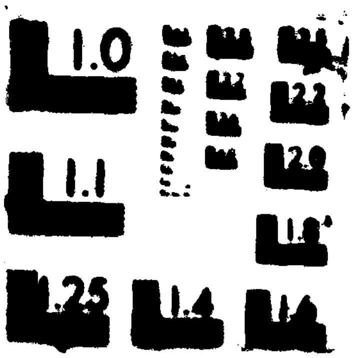
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APPENDIX 6

THE RELATION OF PRODUCTION TO RESEARCH AND DEVELOPMENT IN A GUIDED MISSILE PROGRAM*

A guided missile program that extends from initial conception to operational use may be divided into three distinct but overlapping phases, research, development, and production. Research begins first and is continued concurrently with development; both phases are carried on within the same organization. Toward the end of development, production begins. Ordinarily production is carried on by a separate organization with appropriately contrasting responsibilities. Extensive negotiation and liaison between the two organizations is necessary during the transition from development to production. Since this document is prepared primarily for the use of research and development personnel, the emphasis will be on the production phase and its contrasts and interactions with the preceding phases.

The Research Phase

In a missile weapon system program the purposes of the research phase are to obtain the fundamental information necessary for the preliminary design of the weapon system, to establish the preliminary design, and to support the development by anticipating the need for further basic information and obtaining such information. The problems that motivate the research arise in the broad systems area and all the way down to the areas concerned with the various building blocks. Accordingly, research personnel are found in groups of varying size throughout the research-development organization. The way in which they are affected by the development schedule differs, however, from that for development personnel. There may be specific deadlines when the best information currently available must be furnished to provide a basis for decisions. On the other hand, there are usually no prior deadlines for the completion of research on a given problem, and the personnel are relatively isolated from the details of the development schedule. To an even greater extent than in other phases, reliance for research is placed on "self-starters" who are capable of recognizing problem areas, defining specific problems whose solution will aid the program, and carrying the problems through to practical completion without extensive supervision.

Theoretical research needs little comment beyond that it must be primarily "applied" or, more properly, applyable research. At the beginning, speed and pertinence of the research to the specific decisions required are more important than precision or completeness. Later on, secondary decisions must be made and initial decisions reviewed. Investigation must then be more thorough.

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*This was originally prepared in 1957 at the Guided Missile Research Division of the Ramo-Wooldridge Corporation, with the aid of W.S. Vance and C. Seelig of Ramo-Wooldridge production, as a Technical Orientation Document for incoming members of the USAF ICBM system management team.

Although many of the investigations are not in themselves distinguishable from academic researches, problems that may require a decade or more for any practical application find better directed attention in a separate organization that is not charged with the immediate responsibilities of the missile program.

Experimental investigations frequently involve apparatus and materials similar to those of development, but there is a difference in emphasis. Experimental hardware is in general:

1. Built to prove a principle or afford measurements.

2. Not subject to precise tolerances or required finishes or configurations except as this influences its internal functioning in relation to the objective of the experiment.

3. Not subject to precise weight and performance specifications.

4. Not interchangeable.

5. Not intended to be airborne.

6. Built to engineering sketches or brief informal drawings.

The design, construction, and use of experimental hardware of course require teamwork. Contacts between one person and another are largely informal, with few rigid divisions of responsibility. Select technical personnel are in a larger proportion to the total in research than in any other phases.

The preliminary design of hardware for use in the weapon system is carried out in the research phase. This is frequently referred to as early development.

The Development Phase

The purposes of the development phase are to demonstrate feasibility of the system (that it is usable and sufficiently precise), to attain an interim system reliability sufficient to warrant the initiation of production, and to continue work in those problem areas that need attention but are not appropriately delegated to the production organization.

It is important to note that a large proportion of the hardware manufactured during the development phases is used in the test of the over-all weapon system -- a process that can seldom be allowed to lag because one problem area arises, since the discovery of other equally important problem areas might then be delayed. Thus the attainment of "quick fixes" sufficient to maintain the firing schedule can not be subordinated entirely to the attainment of permanent solutions.

In general, development hardware must:

1. Be capable of being airborne or otherwise usable in the testing of the weapon system.

2. Be interchangeable with only minor adjustments.

3. Incorporate standard parts when they are suitable and will not result in schedule delay.

4. Be made to schedule.

5. Be made to numbered drawings, including layout, assembly, and detail, rather than to sketches.

6. Be made to specifications.

7. Withstand the required environmental conditons.

8. Be accepted or rejected on the basis of inspections and test -- usually on an individual rather than a batch basis.

9. Be reliable.

10. Not be dependent on the skill on any one technician or machinist.

There is an increased use of special tooling, jigs, and fixtures in this phase to the extent that this is justified from the points of view of economy and schedule by the higher rate of manufacture.

From these added requirements on the hardware it is seen that development is a more formal process than research, with more specialization of talent, more definite boundaries of responsibility, and a larger ratio of written to spoken information. In these respects, development is intermediate between research and production. There is a greater use of functional organization as opposed to project organization in development than in research. Instead of the scientist and his technician and machinist help, there is a team composed of development engineers, machinists, and technicians concerned with the manufacture of parts, assembly technicians, inspectors, test engineers, and project control personnel. The project control personnel have the responsibility of following the various items of hardware through the various operations performed, keeping a current record of the location and status of the items, and expediting particular items as needed, according to the judgment of the cognizant development engineer. The man performing a test or inspection of an item will not usually report organizationally to the development engineer responsible for the item. On the other hand, the development engineer plays an important role in establishing what inspections and tests shall be performed, and in most instances has the authority to overrule a rejection or determine what rework should be undertaken. Rejections are on the basis of variations or deviations from stated or implied requirements; the deviations influence performance or reliability whereas the variations do not. The development engineer has a direct responsibility for the hardware schedule, whereas the inspection and test personnel do not.

As the production phase approaches, it is important that some preparation be made for it. This involves making a start on the production specifications and drawings, with such changes being introduced as are immediately necessary for purposes of production. The responsibility for these initial specifications may lie in either organization, but it should be carried out in close cooperation with representatives of the other organization.

The Production Phase

Because the production hardware in a missile program is initially almost identical with the corresponding development hardware, the dividing point between development and production is somewhat arbitrary. A device may be said to be in production when its manufacture by the production organization is undertaken or when a contract for this manufacture is signed. The responsibilities of the production organization are influenced from the beginning by the characteristics that the production hardware must ultimately attain. In general, production hardware must:

1. Be capable of airborne operation or usable in other tests or operations of the weapon system.
2. Withstand the required environmental conditions and be reliable.
3. Be interchangeable.
4. Incorporate standard parts where possible.
5. Be made to schedule.
6. Be made at no more cost per item than is necessary.
7. Be made with no more demand for skilled labor than is necessary.
8. Be made with tooling appropriate to the quantity planned and the firmness of the details of the design.
9. Be based on complete and formal drawings and specifications.
10. Be made with as loose tolerance requirements as possible but according to workmanlike practice.
11. Be accepted or rejected in accordance with rigid inspections and tests.
12. Be amenable to a decreasing number of engineering changes as the production rate increases.

Since the basic design of an item is relatively firm before production begins, and the ratio of effort expended in improving the design to the total effort is smaller in the production organization than in the development organization, the cost of production per item becomes critically important. For this reason, and because of the large number of people involved in production, extensive requirements of skill and training must be avoided except in manning the key positions. There must be definite and detailed delegation of responsibility, and definite lines of authority. Orders and general information must be conveyed primarily in writing rather than orally.

The schedule is an even more important factor in production than in development. If the production rate for any one item is too slow or the quality is unacceptable, there is a corresponding delay in the over-all production schedule of the weapon system. In other words, it is not possible to produce a complete weapon system at a rate greater than that corresponding to the production rate, with acceptable quality, for the most difficult item. Thus there is even more emphasis here on "quick fixes" for the crisis of the moment than in the development phase. The production line must be maintained in operation.

Because of the importance of the production schedule, it is important that the research and development orgainization and the production organization be supplied with separate supporting services. A service group that is responsible to both organizations is likely to be ineffective for production or else will become absorbed by the production organization.

From the added requirements on the product it is seen that organization and methods will tend to be more ponderous for production than for development, but this is by no means uniformly true. Many of the supporting services are themselves not subject to the same restrictions as the direct operations on the product. Tools and test equipment for the production line are not necessarily made in production quantities or with unskilled labor. To deal properly with constantly occurring crises of the production line many of the supporting activities must be capable of flexibility and quick action.

The production drawings and specifications must be complete and detailed. Partly for this reason and partly because of changes in tooling, a new set of drawings, prepared either by the development or the production organization, is necessary at the beginning of production. The men responsible for directing the preparation of these drawings and for any design changes are frequently called product engineers. They may be in either the development or the production organization but must have had experience in production. The drawings consist of layouts, showing completed items with important dimensions, dimensional detail drawings, at least one for each part even if it is a purchased part, and assembly drawings, showing the operations of assembly. All the drawings must be checked for dimensional errors and interfaces. Layout, detailing, and checking are performed by different groups of specialized personnel.

Because the quantities of manufactured items are generally larger in production, when the design is firm, than in development, the cost of expensive tooling is usually offset by a larger saving in labor cost. There is a greater tendency to resort to die casting, stamping, hydroforming, automatic welding or brazing, and other semiautomatic or automatic operations. The greater reproducibility of the product that is obtained by such operations tends to result in improved reliability. The reliability of an item is likely to be less at the beginning of production than it was at the end of development, but gradually will rise to a still higher level.

A design problem that is even more critical in production than in development is the cost of assembly versus the cost of parts. The larger the number of parts, the greater the cost of assembly and the greater the rejection rate resulting from faulty assembly. On the other hand, an item that requires many difficult and precise operations should be divided into a number of machined parts so as to hold down the rejection rates or else should be redesigned so that less difficult operations are adequate.

There is a difference between producing to loose tolerance requirements and producing in an unworkmanlike manner. Loose tolerances, where they are permissible, decrease the cost and production time per item; they are controlled explicitly by the drawings. Workmanlike practice is a more subtle thing that has to do with scratches, quality of surface finish, neatness, and such factors, and is not controlled completely by the drawings. Consequently, a more uniform standard is necessary for this than for tolerances. It is commonly necessary to reject items for unworkmanlike practice even when it does not interfere with function in order to prevent a high rejection rate on items where such practice is critical.

Because of the larger quantities of items involved in production than in development it becomes more feasible to use statistical quality control -- that is, rejection or acceptance of items on a batch basis according to the statistical properties of the batch as estimated by measurements on a sample taken at random from the batch. This is a special technique devised to make some problems of quality control easier. It implies that for each aspect to which the technique is to be applied there is some variable, easily measured for a small sample and behaving according to a simple statistical distribution, from which the probability of an unacceptable condition within the batch is predictable. For example, in an established production process, dimensional measurements on small samples of mating parts will readily permit prediction of the probability of interference or an excessively sloppy fit.

Statistical quality control is likewise applicable in principle to performance parameters so long as small discrepancies are the only concern. There are some aspects, many of them associated with reliability, that require 100-percent testing, or equivalent techniques, regardless of the production rate. The probability of cracks or other flaws in a batch of castings cannot ordinarily be estimated by inspection of a small sample; yet one such flaw in the batch may be intolerable. Badly soldered joints do not ordinarily lend themselves to statistical quality control.

When an item is rejected, its ultimate disposition -- whether to rework, use as is, or scrap -- is ordinarily decided by a material review board, consisting of representatives from various production organizations, product or liaison engineers, and the contracting agency such as the Air Force.

Because of the large amount of planning, paper work, coordination, and cost necessary to effect a design change in production, special techniques of controlling design changes are used. Ordinarily, the primary control is the block system, according to which the production quantities are divided into successive groups, called blocks. Ordinarily the size of the block increases as production progresses. Changes for improvement of function are incorporated only at the beginning of the block unless they are mandatory changes, that is, changes that are essential for function or reliability. Minor changes for improvement of manufacturability may be introduced at any time at the discretion of those who have responsibility for the production schedule. The final decision as to whether changes recommended during a block are mandatory, nonmandatory, or for improved manufacturability is made by change control board with representatives chosen similarly to those on the material review board. The change control board also rules on effectivity -- the date on which the change becomes effective. In deciding the effectivity, it is of course necessary to determine by what date any necessary new materials or parts can be obtained.

When a radical change is introduced late in production, it may be advisable temporarily to set up a modification center so as to avoid disrupting the production line. The missiles are completed without the change and then are sent to the center for modification. Retrofit on the missiles completed prior to the design change is carried extensively only in special cases, since stockpiling is less extensive than with other weapons.

There may also be a reliability board, or committee, which takes the lead in monitoring rejections, particularly those that are important to reliability, in obtaining detailed diagnoses and histories, and in prodding for corrective action to prevent recurrence.

At the beginning of production, the responsibility for function of the product ordinarily remains temporarily with the development organization, whereas the responsibility for manufacturability, schedule, and other problems related to the product lies with the production organization. It is usually not feasible to let the development organization have detailed control over production in an operation of any size. Personnel who are familiar primarily with the traditions of development and, in particular, of research, frequently have too little interest in the problems and techniques of production to carry full responsibility for it. The converse of this is also true.

A representative production organization chart is shown in Fig. 1. The six sets of functions at the bottom are staff functions. As a practical matter the organization in production, as in development, will be influenced somewhat by the respective talents of the key men available.

Ordinarily the Quality Control preferably should report to the same level as Production Engineering and Production (Fig.1). Within quality control, there is no responsibility for schedule. The sole responsibility of Quality Control is to accept or reject in accordance with established standards. It has no role in establishing these standards except, perhaps, in connection with matters of workmanlike practice.

If, as is common, the initial production drawings are controlled by the development organization, the first step in preparing for production is the transfer of redline drawings (or, more aptly, red line prints of the drawings) to the production organization. These prints are made before the drawings are checked and are used only for planning, not for the dimensioning of tooling. Blue line drawings are transmitted later when the design details for initial production are firm and checking has been completed.

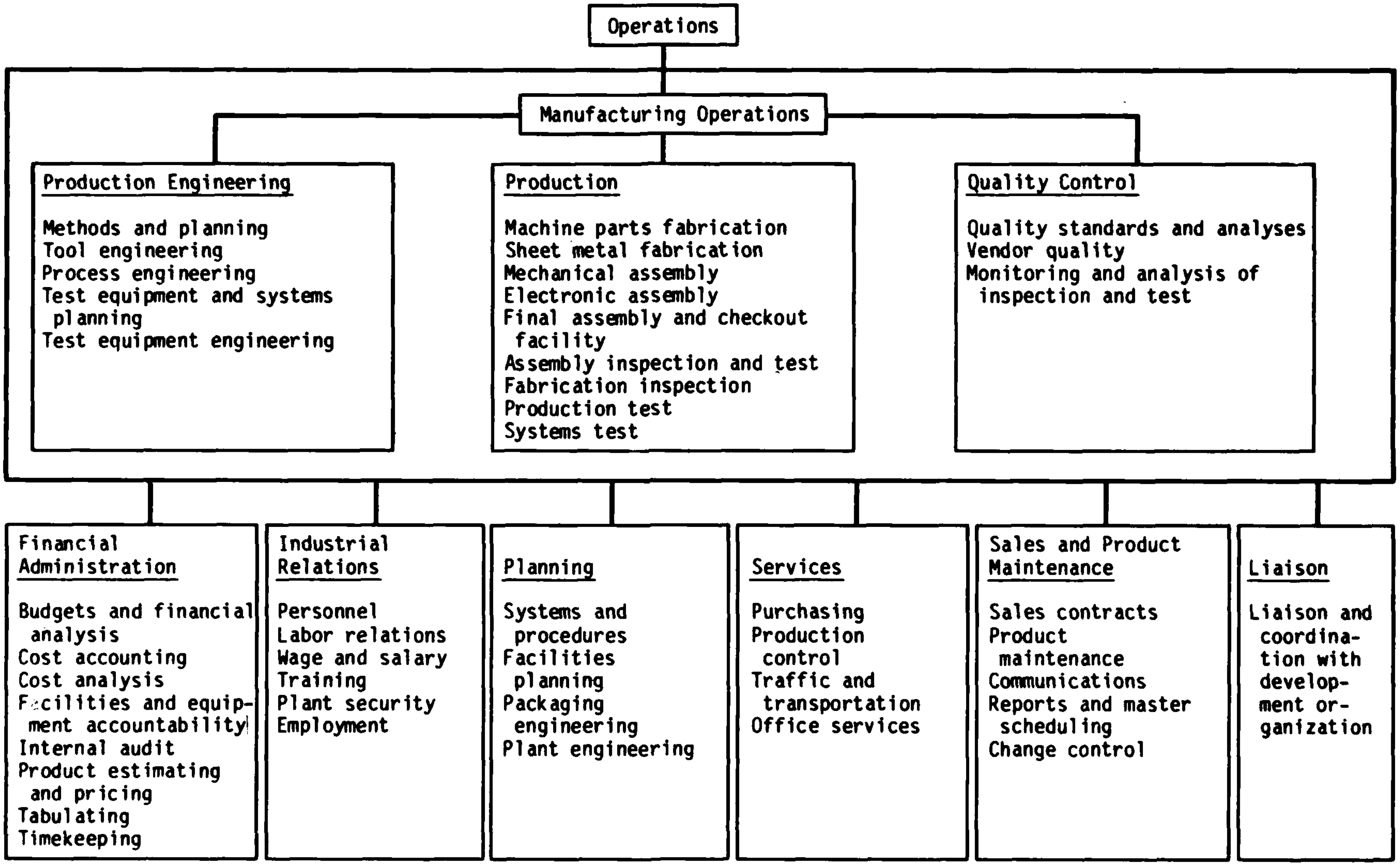

Figure. 1 A Representative Production Organization

On the basis of red line drawings, initial planning for tooling, test equipment, plant layout and equipment, time standards, and manpower is carried out. Costs per item are estimated and compared with data in the standards manual. A detailed schedule is made out.

In a missile program, early production or late development is often referred to as pilot production.

Guided Missile Versus Other Military Production

Missile production differs from other military production primarily in the amount of field testing that is necessary, in the relative infirmness of the design at the beginning of production despite a relatively long and intensive development phase, in relative complexity, and in the amount of checkout equipment required. Since the missile is unmanned and ordinarily nonrecoverable, most of the development and early production output is used exclusively in field testing. This has some influence on the equipment included even in the production versions. Because of rapid obsolescence, stockpiling is small.

Military Versus Commercial Production

Military production, as contrasted with commercial production, is ordinarily more complicated, is based on design that is less firm, and is subject to more engineering changes, especially in peacetime. Production and development overlap, and changes are introduced in both phases as the state of the art develops, for it is intolerable to be caught in a war with only an obsolete model available. The pressure for attaining reliability is high. Although the ultimate planning is not known at the beginning of production, purchase of the block currently in production is assured. Since competition is not so important an incentive in military as in commercial production, the designs are subject to extensive military specifications, and the contracting agency has inspectors in the production plant to ensure that the design and workmanship are in accordance with the specifications.

Although the profit margin is lower in military than in commercial production, the contracting agency assists in one way or another in providing buildings, facilities, and needed equipment. Thus the capitalization may tend to increase more rapidly than it does in commercial production.

APPENDIX 7

SYSTEM ENGINEERING

The objectives of this appendix are to illustrate briefly the character of system engineering, review some missile system engineering techniques that relate to the interpretation of parameter tolerances in environmental test, and discuss the unique and peculiar role of the shock and vibration engineer.

Much that has been written or implied about system engineering since the middle fifties, when the phrase first became popular, is misleading.

At one extreme, universities have on occasion devised courses and curricula labelled system engineering. Apart from a need to differentiate more according to the type of system under study, the main point is that engineering is a matter of teamwork and decision making. The professors are doing what they do best, and for most part what they should be doing -- teaching applyable science and mathematics that may be useful as a foundation for decision making later.* Engineering decision making is a more conscious and obvious part of development and production, which were discussed in the last appendix, than research. For the most part it must be learned in industry.

At another extreme, it has been claimed that, whereas ordinary engineering is performed by specialists, system engineering is performed by generalists who are competent in many fields. No systems effort would be able to get under way very fast or very far if it depended on this approach, which has at best only marginal validity. For example, consider a missile (perhaps ICBM) organization, compartmented into various departments labelled system analysis, airframe, aerodynamics, rocket engines, guidance, control, environmental test, and so on. For the most part, the effort in all of these departments is carried out by specialists with an exaggerated (no adverse critism intended -- this may usually be necessary for competence and dedication) impression of the importance of their particular specialties to the overall system. Their efforts are directed toward a common objective, not primarily by generalists of the type suggested above, but by specialists in one field or another who have acquired an understanding of the roles of the others in the overall effort, and an appreciation for the tradeoffs and compromises between them that are necessary for a successful system product. They are not necessarily capable of doing the work of the other specialists for them, nor should they be, but they appreciate technical depth because of their own prior specialist experience.

Performance Tolerances

The example of missile guidance permits making some clear distinctions between performance degradations and more catastrophic reliability problems.

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*C. T. Morrow, "What an Engineer Learns in Industry", Journal of Engineering Education, Vol. 59, No. 9, May 1969, pp 1025-1028.

Performance tolerances should be treated differently in environmental test depending on whether they are most directly related to one or the other. The distinctions still hold to some degree in avionics. First, in the missile guidance analysis, an rms miss distance is agreed on, based on the radius of effectiveness of the warhead and the number of marginally effective flights that can be tolerated. Then if the state-of-the-art of component development is such that the system can be successful, error is apportioned among the subsystems, equipment and components.

The first system tasks are concerned almost entirely with nominal performance parameters of subsystems equipments and components and with permissible performance degradations. Consider the drift rates of gyroscopes and accelerometers -- their tendency to generate false signals that appear like those of actual angles, actual rotation rates, or actual accelerations or components of gravity. The first system task associated with these is to determine from the system mathematics an error coefficient for each by itself -- a ratio of miss distance to error -- there is usually a more or less linear relationship. The effect of random simultaneous errors in a population of missiles is, however not a linear summation -- part of the time an error of one type will actually compensate in part for an error of another type. Usually, all distributions are assumed to be Gaussian. The net effect is that the root mean square miss is the square root of the sum of the squares of the products of the various rms errors by their respective miss coefficients.

This establishes the miss distribution for any population of errors but does not accomplish the reverse. Here is where engineering really comes in, with decisions that must be based as much on component state-of-the-art as on scientific or mathematical principles. It makes little sense to place close tolerances on the accelerometers and loose tolerances on the gyroscopes if this would make the gyroscopes much more difficult to develop. The optimum assignment of tolerances is one that distributes the development burden evenly. The initially assigned tolerances are rms tolerances, suitable for acceptance and rejection of components by production batch, but not for individual acceptance and rejection typical of development and low-rate production. For this purpose they must be converted, somewhat arbitrarily, to absolute limits, perhaps by multiplication by a factor of 2 or 3, yielding, except with large instrumentation uncertainties, truncated Gaussian distributions.

Now consider the reliability problems, which are also an important aspect of development even though their solution is less straightforward -- less a matter of proof than competent handling of evidence. In comparison, they have a nonlinear (often undefinable) and catastrophic relation to miss distance or completion of a mission. Their essence, whether by way of mechanical failure or an extreme tolerance value or both, is to convert the system under study to a different system, without the same number of parameters, and without the same capabilities. They have no relation to Gaussian distributions, since there is neither a predictable relationship to miss distance nor any significant tendency for one problem to compensate for another. They are subject to a different kind of statistics, more related to the reliability product formula of the next appendix.

For the shock and vibration engineer and the designers he may be working with, this distinction is important primarily in respect to accelerated test at increased severities of excitation. Such test can be useful for reliability problems by reducing test time and encouraging safety margins for reliability type failures. But it may also lead to parameters out of tolerance -- of a performance degradation type. These should not be taken at their face value but corrected according to a suitable scaling law if one can be established. Furthermore, for the latter discrepancies, one or two test items may be sufficient for statistical significance.

In avionics, the distinction is not quite so clear cut, because we can not be so callous as to consider a small percentage of aircraft or even aircraft missions to be expendable because of parameters slightly out of tolerance. Yet it remains true that some discrepancies have a more or less linear relationship to severity of environment, and are subject to simple scaling laws, whereas others are nonlinear and catastrophic.

Role of Shock and Vibration Engineer

The discussion above should provide some feeling for the tradeoffs and related decision making characteristic of system engineering. They are not typical of shock and vibration engineering as part of the system effort at the present time, which is governed instead primarily by literal interpretation of performance specifications and literal interpretation of environmenal specifications. The latter are an official subject for negotiation at the beginning of a program, with some shock and vibration engineers present, but with too little known for definition of tradeoffs, with no system analysis except perhaps for the product law analysis underlying reliability apportionment, and with decision more by majority vote than responsibility assignment and corresponding engineering judgment. The reliability apportionment does not distinguish between environmentally induced failures (which do not accurately follow the product law) and failures that are independent of the environment, and in any case serves no purpose for the shock and vibration test engineer unless testing is to be statistical -- it has no definite relationship to testing for design deficiencies. The shock and vibration engineer tends to be confined to the beginning and end of a program and excluded, except for occasional early environmental testing, from the main course of the development where his tradeoffs and negotiations could be more useful.

APPENDIX 8

ORIGINS OF STATISTICAL RELIABILITY TESTING

Section 5.11 of Chapter 5 is a commentary on Col. Swett's presentation on statistical reliability testing. The purpose of the present appendix is to review some of the history leading to the establishment of MIL-STD-781, clarify some concepts, show the confusion that resulted from neglect of technical management aspects, and point to a dramatic example of the risks associated with pursuing too blindly the objective of absolute proof of design adequacy.

The practice of statistical reliability testing survives today in connection with airplane avionics. It orginated but was largely discarded in the context of guided missiles, whose reliability had become a delicate political problem by the middle fifties. Both customer and contractor managements were under pressure to establish a crash effort to solve the missile reliability problem. The only new idea for a foundation for such an effort came from the work of R. K. Lusser. In two reports, he brought to the attention of statisticians and guided missile engineers the product law for relating the reliabilities of a system to the reliabilities of its subsystems, equipments, components and parts, on an implicit assumption of <u>complete independence of failure rates</u>.

The reliability of a system of two components is given by

$$R = 1-F_1-F_2+F_{12}, \qquad (10)$$

where F_1, is the probability of failure of component 1, F_2 is the probability of failure of component 2, and the probability F_{12} that both fail in one mission is subtracted because it is already contained once in each of the other probabilities. The assumption of independence of failure rates is

$$F_{12} = F_1F_2, \qquad (11)$$

which leads to

$$R = 1-F_1-F_2-F_{12} = (1-F_1)(1-F_2) = R_1R_2, \qquad (12)$$

where R_1 and R_2 are respectively the reliabilities of components 1 and 2. More generally, for N components having independent failure rates, the system reliability is given by the product law

$$R = R_1R_2 \ldots R_N, \qquad (13)$$

which requires that the component reliabilities become closer and closer to perfection (unity) as their number N increases and therefore that increasingly larger numbers of each be manufactured for statistically significant test. It holds indeed if no failures are environmentally induced.

Now return to Equation (10). Suppose that there is no unreliability except on occasional missions when there is a shock so severe that component 1 fails:

$$F_{12} = F_2 = 0, \tag{14}$$

which leads to

$$R = R_1. \tag{15}$$

This can be generalized to N components as a weakest link formula, much less demanding on the component reliabilities. In practice, the truth is somewhere in between Equations (12) and (15).

In any event, Equation (13), taken as an axiom, caught the imagination of many statisticians and engineers who, with some initial encouragement from management, came to feel that they had an uncontestable mandate to solve the reliability problem using it as a foundation. First, in the well-founded tradition of system engineering, they established a reliability apportionment procedure based on equitable distribution of the development burden.

Then they demanded a statistically designed verification program with progressively larger numbers of tests and correspondingly larger numbers of test items. Finding the simplicity and beauty of the statistical logic irresistible, they rushed on their way to inevitable frustration, with no regard for schedule or cost -- they were soon demanding a much higher production rate for statistically significant test than had been planned for operational purposes. They even talked of stopping development early in the schedule in order to provide homogeneous samples for test, thereby potentially obstructing the engineering effort essential to reliability. They included comprehensive environmental simulation as part of their plan, but their focus was entirely on statistical errors, to the exclusion of systematic. They soon lost interest in the actual environment, requiring only that the environment be specified, not necessarily with any careful engineering judgment, for a major objective was to make the reliability problem as independent of engineering as possible.

Management could not accept their recommendations, but did not have time to sort out the issues and redirect the movement. The statistical reliability people felt understandably frustrated and betrayed -- they had been given a clear mandate to solve the problem and had had that mandate withdrawn, they thought, as soon as they came near to the solution. Actually, much of what they came up with had very little to do with the practical problem. Eventually, the reliability apportionment procedure was accepted, but the verification procedure was rejected for missiles except for the overall system and major subsystems.

The thrust of the reliability movement became diverted from missile airborne equipment to avionics. A case could be made for testing small numbers of equipment many times, because the equipments were not conceived as short lifetime items. One might argue that the small number of units tested might be stronger or weaker than the populations from which they were taken, but eliminating the overwhelmingly excessive costs of manufacture for test made the program marginally feasible. Focus shifted from reliability per se to mean time between failure (MTBF). In MIL-STD-781, the vibration environment was made so benign that it was not worth the effort of setting up for test.

The statistical reliability movement had got under way originally with no attention to technical management aspects at all, and with everything gambled on a mathematical concept. For example, there was no discussion of why one would want to verify reliability at other than the system level as opposed to testing for design inadequacies, or how deep into subsystems and components one should do it. It seemed to be assumed that if subdivision was possible, a need for statistical verification was an incontestable consequence. No limitations of specifications other than the statistical were considered important. The problem was conceived as statistical, legalistic and moral, with engineers and technical managers as the culprits. This was the ultimate reduction to absurdity of the concept of the infallible verification of design adequacy.

Col. Swett has succeeded in putting engineering back into MIL-STD-781 to the extent of providing for more realistic environments, and he has devoted much of his attention to reliability growth during the tests. It may well be that the value of the specification in the future will be found more in growth than in verification, with more engineering involvement to determine what aspects of a design are most amenable to growth during long-term testing, and still more participation to ensure that growth takes place. While this report is critical of many aspects of statistical reliability testing it is not intended as an adverse criticism of other responsibilities of reliability engineers.

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18. C. T. Morrow and D. E. Riesen, "A Shock Spectrum Computer for Frequencies Up to 2000 cps", J. Acous. Soc. Amer., Vol. 28, No. 1, Jan. 1956, pp. 93-101. The first <u>electronic</u> shock spectrum computer, now only of historical interest. It demonstrated that analog computation of shock spectra from shock time histories recorded on magnetic tape was feasible, and that residual spectra could be distinguished from initial or maximax.

19. C. T. Morrow, "The Shock Spectrum - a Means of Stating Mechanical Shock Requirements". Electrical Manufacturing, Vol. 64, No. 2, Aug. 1959, pp. 121-127, 176. Compared the spectrum to the pulse shape as a criterion of

severity. There is evidence now that if the pulse shape is not also recommended, as a secondary requirement, there may be benefits from placing tolerances, directly or indirectly on the phase aspect of the spectrum.

20. R. D. Mindlin, F. W. Stubner and H. L. Cooper, "Response of Damped Elastic Systems to Transient Disturbances", Proc. Soc. Exp. Stress Anal., Vol. 5, No. 2, 1948, pp. 69-87.

21. J. M. Frankland, "Effects of Impact on Simple Elastic Structures", Proc. Soc. Exp. Stress Anal., Vol. 6, No. 2, 1949, pp. 7-27.

22. L. S. Jacobsen and R. S. Ayre, "A Comparative Study of Pulse and Step-Type Loads on A Simple Vibratory System", ONR Technical Report 16, Structural Dynamics, Contract N6-ORI 154, Task 1, Stanford University, 1952.

23. N. B. Brooks and N. M. Newmark, "The Response of Simple Structures to Dynamic Loads", ONR Technical Report, Contract N6 ori (06), Task Order VI, Project NR-064-183, University of Illinois, April 1953.

24. C. T. Morrow and H. I. Sargeant "Sawtooth Shock as a Component Test", J. Acous. Soc. Amer., Vol. 28, No. 5, Sept. 1956, pp. 959-965. The origin of the sawtooth shock test, almost unique for its smooth residual spectra, free of nulls. In original application, the pulse was recommended as a practical means of achieving a specified minimum spectrum. More recent practice has followed two divergent policies. One is to specify the spectrum only, more or less in accordance with Paper 19, but with positive and negative tolerances. The other is to specify pulse shape only, following the example of the applicaton of Papers 20-23, and apply positive and negative tolerances relative to the nominal pulse, in the acceleration-time domain.

25. C. T. Morrow and R. B. Muchmore, "Shortcomings of Present Methods of Measuring and Simulating Vibration Environments", Shock and Vibration Bulletin 21, Nov. 1953, pp. 89-96, also J. Appl. Mech., Vol. 22, No. 3, September 1955, pp. 367-371. The origin of statistical concepts in vibration data reduction and of the random vibration test. The paper became controversial for the greater part of a decade, not because any concepts were actually invalid or irrelevant, or because any derivations were in error, but because random vibration test facilities and convenient instruments for obtaining power spectra were not generally available. Consequently, the doubt shed on existing test practices was not compensated by any immediately practical alternatives. Papers 34-42 below are examples of the reaction. As Paper 5 provided the first example of equivalence for design, this paper was the first to discuss theoretical equivalence for test, primarily to show the difficulty of the problem. Subsequently, of necessity, equivalence of test conditions in terms of anticipated damage became a subject for intensive search.

26. S. O. Rice, "Mathematical Analysis of Random Noise", Bell Syst. Tech. J., Vol. 23, July 1944, pp. 282-332 and Vol. 24, Jan. 1945, pp. 44-156. Reprinted in N. Wax, Selected Papers on Noise and Stochastic Processes, Dover, 1954. The classic paper on its subject and the theoretical foundation for Paper 25.

27. C. T. Morrow, "Significance of Power Spectra and Probability Distributions in Connection With Vibration", Bulletin 28, Shock, Vibration and Associated Environments, pp. 171-176. Emphasis on the greater practical importance to vibration of the spectrum, as opposed to the distribution, which was given equal weight in Paper 25 and is the more fundamental concept in statistics.

28. B. M. Hall and L. T. Waterman, "Correlation of Sinusoidal and Random Vibrations", Bulletin 29, Shock, Vibration and Associated Environments. The first paper to consider equivalence between random vibration and the swept sinusoid as opposed to periodic excitation at a fixed frequency.

29. C. T. Morrow "Averaging Time and Data Reduction Time For Random Vibration Spectra", Part I, J. Acous. Soc. Amer., Vol. 30, No. 5, May 1958, pp. 456-461. A supplement to Paper 25, pointing out the tradeoff between statistical significance and resolution.

30. C. T. Morrow, "Averaging Time and Data Reduction Time For Random Vibration Spectra", Part II, J. Acous. Soc. Amer., Vol. 30, No. 6, June 1958, pp. 572-578. An analysis of the time required to obtain an entire power spectrum by analog computation, and some measures that could be taken to shorten the operation. The problem was eventually avoided by application of digital circuitry.

31. C. T. Morrow and D. E. Riesen, "A Random Vibration Facility For Reliability Testing", Fundamentals of Guided Missile Packaging, Chapter 5, Section 3A. The first facility for random vibration testing to specification, preceded, at the Jet Propulsion Laboratory, by a facility for experimental playback of missile flight vibration recorded on tape--for experimental investigation of equivalence between random vibration and the swept sinusoid, although the term equivalence was not actually mentioned. The specification test facility was essentially complete, with electronic random noise source, multi-kilowatt power amplifier, limiter to protect the shaker armature from bottoming, rapid shutdown capability in the event of power amplifier malfunction, and a rudimentary equalizer. Equalization became a subject for intensive investigation, as exemplified by Papers 32, and 33, becoming eventually automatic, and, more recently, digital.

32. R. W. Blevins and J. S. King, "Development and Use of A Shaping Network For Complex-Wave Testing", Shock and Vibration Bulletin 23, June 1956, pp. 102-110.

33. J. A. Ross, "A New Method For Equalization in Random Vibration Testing", Bulletin 27, Shock, Vibration and Associated Environments, Part II, June 1959, pp. 121-158.

34. R. S. Bradford, "To What Extent is Missile Vibration Truly Random?" Shock and Vibration Bulletin 24, Feb. 1957, pp. 315-317.

35. C. T. Morrow, "Why Test With Random Vibration?" Shock and Vibration Bulletin 24, Feb. 1957, pp. 329-332.

36. C. R. Bumstead, "The Pros and Cons of Random vs. Sinusoidal Testing", Shock and Vibration Bulletin 24, Feb. 1957, pp. 333-334.

37. F. Mintz, "Random Shake--An Obnoxious Conglomerate or Delightful Mixture?" Shock and Vibration Bulletin 24, Feb. 1957, pp. 335-337.

38. F. A. Jennings. "Practical Applications of Random Vibration Testing", Shock and Vibration Bulletin 24, Feb. 1957, pp. 351-352.

39. A. J. Curtis, "Some Practical Objectives in Random Vibration Testing", Shock and Vibration Bulletin 24, Feb. 1957, pp. 351-352.

40. R. C. Lewis, "Performance Limitations of Available Equipment for Random Vibration Testing", Shock and Vibration Bulletin 24, Feb. 1957, pp. 353-355.

41. D. T. Sigley, "Sinusoidal Vibration Testing is at Present Adequate", Shock and Vibration Bulletin 24, Feb. 1957, p. 157.

42. R. E. Blake and M. W. Oleson, "Substitutes for Random Vibration Testing", Shock and Vibration Bulletin 24, Feb. 1957, pp. 338-343.

43. C. T. Morrow, "Random Vibration", J. Acous. Soc. Amer., Vol. 32, No. 6, June 1960, pp. 742-748.

SPECIFICATIONS AND RELATED DOCUMENTS

Several of the Government specifications or standards are undergoing revision and/or change of official status and official scope of applicability. Innovation is slow, because of the weight given to past tradition, and contractor response to innovative requirements and lags behind Government ultimate intent, partly because of instrumentation lead times and partly because of the constraints of existing contracts. Contracts commonly provide for using the latest revision, at any time during the contract period, of any specification or similar document referred to, but to do not provide for abandoning one specification in favor of another.

This is a selection or pertinent documents out of a very large list. Just what specifications apply under a specific contract depends very much on the particular negotiators.

1. Environmental Data Bank Index, Unclassified Entries, M. B. Gens, Sandia Laboratories Albuquerque, New Mexico. Also available through SVIC.

2. Report SLA-73-0456, "Current Predictive Models of the Dynamic Environment of Transportation," J. T. Foley, M. B. Gens and C. F. Magnuson, Sandia Laboratories, Albuquerque, New Mexico.

3. SPHE - Guide for the Selection of Mechanical Devices for Monitoring Acceleration Induced by Shock and Vibration--MH19.1. A Society of Packaging and Handling Engineers Standard, under negotiation.

4. MIL-STD-1367, Military Standard, Packaging, Handling, Storage, and Transportability Requirements (for Systems and Equipments). Covers an authorized management system.

5. DATA ITEM 11-025 (Army AMC). Among other considerations, requires packaging engineer and contents designer initiate communication at receipt of contract. This must be provided for in the proposal.

6. MIL-STD-1319A (Proposed) Military Standard, Item Characteristics Affecting Transportability and Packaging and Handling Equipment Design. Primariily an itemization of characteristics of contents.

7. MIL-P-9024, Transportability. Applies primarily to container but partly to fragile contents.

8. MIL-STD-648 (Proposed), Design Criteria for Specialized Shipping Containers. Under tri-service negotiation as the eventual standard or specification for Government shipping containers.

9. Status Report on Proposed MIL-STD-648, "Design Criteria for Specialized Shipping Containers," R. E. Seely, Naval Ammunition Depot, Earle, N. J.

10. OR-11, Development of Packaging, Handling, Storage and Transportation Systems for Weapons, Naval Ordnance Requirements. Presumably to be replaced by MIL-STD-648.

11. MIL-HDBK-304, Military Standardization Handbook, Package Cushioning Design.

12. U. S. Army Rocket & Missile Container Engineering Guide, U. S. Army Missile Command, Redstone Arsenal. A detailed design manual.

13. MIL-STD-794D, Parts and equipment, Procedures for Packaging and Packing of.

14. MIL-C-172C, Cases; Bases, Mounting; and Mounts, Vibration (for Use with Electronic Equipment in Aircraft). Primarily a specification of quality requirements of isolators as purchased parts, rather than of the functional (isolation) requirements for use in a system.

15. MIL-M-17185A, Resilient Mounts (Shipboard) and Tests.

16. MIL-P-26514, Polyurethane Foam, Rigid/Elastic, for Packaging.

17. MIL-STD-108D, Enclosures for Electronic and Electrical Equipment.

18. Shipping and Storage Container Specification for Phoenix Missile All-up-Round Container, Naval Missile Center, Point Mugu, California. A document for in-house application.

19. Technical Publication TP-72-41, Evolution of Packaging Design in Support of Air Launched Weaponry aboard the Attack Carrier (Airtask A537537132254), C. G. Gerblick, Naval Missile Center, Point Mugu, California.

20. MIL-STD-810C, Environmental Test Methods for Aerospace and Ground Equipment. Revised, partly with intent to transfer packaging requirements to MIL-STD-648. Under tri-service coordination.

21. MIL-E-5400E, Aircraft Electronic Equipment. Primarily for design.

22. MIL-E-5272-C, Environmental Testing, Aeronautical and Associated Equipment.

23. MIL-E-5422, Environmental Testing, Aircraft Electronic Equipment.

24. MIL-T-21200, Particularly for Ground Support Equipment.

25. MIL-E-4970A, Environmental Testing, Ground Support Equipment.

26. MIL-E-16400F, Electronic Equipment, Naval Ship and Shore.

27. MIL-T-17113, Shock, Vibration and Inclination Tests.

28. MIL-STD-202C, Test Methods for Electronic and Electrical Component Parts.

29. NRL Report 7396, "Shipboard Shock and Navy Devices for its Simulation," E. W. Clements.

30. MIL-S-910B, Shipboard Equipment Class HI (High-Impact), Shipboard Application, Tests for.

31. MIL-E-4456, Variable Duration Shock, Method and Apparatus.

32. MIL-STD-167, Mechanical Vibrations of Shipboard Equipment.

33. MIL-STD-446, Environmental Requirements for Electronic Component Parts.

34. MIL-STD-1365, Military Standard, General Design Criteria for Handling Equipment Associated with Weapons and Weapon Systems.

35. MIL-STD-785, Reliability, Procedural and Organizational.

36. MIL-STD-756, Reliability Predictions.

37. MIL-STD-781, Reliability Demonstrations.

38. DOD Directive 5000.40, Reliability and Maintainability.

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